Downlink Macrodiversity in Cellular Network A Fluid Analysis

Jean-Marc Kelif[1], Eitan Altman[2]

[1] France Telecom Research and Development Issy Moulineaux, France
[2] INRIA Sophia Antipolis, France

jeanmarc.kelif@orange-ftgroup.com, eitan.altman@sophia.inria.fr

Abstract. This paper proposes an analytical study of the downlink macrodiversity. Considering two macrodiversity links, we first show that the downlink macrodiversity induces a specific load in the cell. We establish an explicit expression of this one, and show that macrodiversity increases the total cell's load. The network's fluid analysis we propose enables to calculate the load of a cell and to quantify the impact of macrodiversity. We show that macrodiversity decreases the capacity of a cell. We generalize the analysis, considering a macrodiversity with a great number of base stations of the network.

1 Introduction

The studies related to macrodiversity were mainly done for the uplink [7] [8]. Hanly [7] described macrodiversity as a scheme in which the cellular structure of a wireless communication network is removed and user is jointly decoded by all receivers in the network. Hiltunen and de Bernardi [4] developed a downlink analysis of the macrodiversity to estimate a CDMA network's capacity. Their analysis considers the macrodiversity use to maintain the SIR target of mobiles in soft/softer handover with two base stations. It is well known that downlink macrodiversity induces an extra load that can be considered as the "price" for obtaining the macrodiversity gain. In this paper we demonstrate why there is an extra load. We give its analytical expression and quantify with a high accuracy the impact of macrodiversity. Afterward, we propose a model which allows calculating analytically that extra load. This model considers the network as a continuum of base stations and *allows calculating the influence of any mobile* in a cell*, whatever its position*. For clarity of presentation, this paper is focused on CDMA networks. However, the analysis we develop can be used for other technologies such as OFDMA (see remark at the end of the section 2.1).

The paper is organized as follows. In Section 2 we introduce the interference factor f_i^{DL} which characterizes the "weight" of the network, on a given cell. We show that mobiles in macrodiversity induce a positive specific load L_{MD}. In Section 3, we express the cell's load, using a fluid model of the network [9][11]. This approach considers the network as a *continuum.* It can be applied to any frequency reuse 1 networks, such as OFDMA or CDMA ones. In Section 4, we establish the macrodiversity decreases a cell's capacity. In Section 5, we generalize the macrodiversity analysis to a whole network, and show it always induces a decrease of the capacity. In Section 6 we conclude.

2 Cellular network Analysis

2.1 Network analysis

We use the model similar to [4]. Let us consider a mobile connected to the base station *b* of a network of N_{BS} base stations, each BS_j defining a cell *j*. We express that the *Signal to Interference Ratio (SIR)* received by a mobile has to be at least equal to a minimum threshold target value γ_i [4] [5]. Each mobile uses only one service. Using the equation of the transmitting traffic channel power [4] for the downlink, the following condition has to be satisfied:

$$\frac{P_{ib}\, g_{ib}}{\alpha I_{\text{int}} + I_{ext} + Noise} \geq \gamma_i \tag{2.1}$$

where P_{ib} is the useful transmitting power coming from the base station *b* towards the mobile i belonging to the base station *b*, and g_{ib} is the pathloss between the base station b and the mobile *i*, I_{int} is the interferences due to the common channels and the traffic channels of the other mobiles located in the cell *b*, and I_{ext} is the interferences due to the other base stations of the network, γ_i represents the level of the signal to interference ratio target for the service used by the mobile *i* for the downlink, *Noise* stands for the level of noise floor at the mobile receiver, and α the orthogonality factor, and $g_{j,i}$ the pathloss between the mobile i and the base station *j.* Introducing P_b the total transmitting power of the base station *b*, including the common channels assumed as orthogonal, and $\beta_i = \dfrac{\gamma_i}{1+\alpha\gamma_i}$. For each mobile *i* belonging to the cell b, we define the parameter f_i^{DL} , as the ratio between the total power P_{ext} received by the mobile *i* coming from the other base stations of the network to the total power P_{int} received by its serving base station *b*:

$$f_i^{DL} = \frac{P_{est}}{P_{\text{int}}} = \frac{1}{P_b g_{ib}} \sum_{j=1, j\neq b}^{N_{BS}} P_j g_{ij} \tag{2.2}$$

We express from (2.1) the minimum needed traffic channel transmitting power as:

$$P_{ib}g_{ib} = \beta_i(\alpha P_b g_{ib} + f_i^{DL} P_b g_{ib} + Noise) \tag{2.3}$$

Remark
Though our analysis is focused on CDMA networks, the model we develop is still valid for cellular technologies without internal interference, providing that $I_{\text{int}} = 0$. It can be applied, in particular, to frequency reuse 1 networks based on other technologies, such as OFDMA.

2.2 Downlink macrodiversity analysis

Base station transmitting power
Our approach is inspired by [4]. The downlink *macrodiversity* allows a mobile to use the signals received from more than one base station to reach the requested SIR target. We establish the analytical expression of the cell's load, taking into account the macrodiversity with two base stations, and show that the macrodiversity *always increases* the load. A mobile *i* in macrodiversity is connected to two base stations *b* and *l*. *b* is defined to be the base station with larger SIR. We express that the power control tries to maintain the SIR target γ_i. We denote $\gamma_{i,l}$ and $\gamma_{i,b}$ the SIR received by mobile *i* coming from base stations *l* and *b*, and we assume that:

$$\Omega_i = \frac{\gamma_{i,l}}{\gamma_{i,b}} \le 1 \tag{2.4a}$$

is a constant. The SIR target is:

$$\gamma_i = \gamma_{i,b} + \gamma_{i,l} \tag{2.4b}$$

Considering a mobile belonging to the BS *b* and in macrodiversity with the BS *l*, and introducing $\kappa_i = \frac{\gamma_i}{1 + \Omega_i(1+\gamma_i) + \alpha\gamma_i}$ (2.4c), the expression (2.3) becomes, for a mobile *i* in macrodiversity:

$$P_{ib} = \kappa_i(\alpha P_b + f_i^{DL} P_b + Noise/g_{ib}) \tag{2.4}$$

Let there be *N* mobiles in a cell *b*, *M* among them are in macrodiversity with the BS *l*. As a consequence, in the macrodiversity zone we can consider *M* mobiles belonging to the BS *b* and *P* mobiles belonging to the BS *l* in macrodiversity with *b*. These last ones also receive a signal from the BS *b*. Denoting P_{CCH} the power dedicated to the common channels, the total transmitting power of the base station *b* can be expressed as the sum of all the transmitting powers channels:

$$P_b = \sum_{i=1}^{N-M} P_{ib} + \sum_{j=1}^{M} P_{jb} + \sum_{k=1}^{P} P_{kb} + P_{CCH} \tag{2.5}$$

Hypothesis

For a homogeneous repartition of mobiles in the macrodiversity zone, we can assume that *M=P*. And statistically, due to the homogeneity of the mobiles repartition, the total power dedicated to the mobiles *M* should be the same as the total power dedicated to the mobiles *P*. So we can write:

$$\sum_{j=1}^{M} P_{jb} = \sum_{k=1}^{P} P_{kb} \tag{2.6}$$

The expression (2.5) can be rewritten:

$$P_b = \sum_{i=1}^{N-M} P_{ib} + 2\sum_{j=1}^{M} P_{jb} + P_{CCH} \tag{2.7}$$

The power P_{CCH} dedicated to common channels is assumed as proportional to the power of the base station so we have $P_{CCH} = \varphi P_b$. Denoting:

$$A = \sum_{i}^{N-M} \beta_i \, Noise/g_{ib} + 2\sum_{j}^{M} \kappa_j \, Noise/g_{jb} \tag{2.8a}$$

and

$$L = \sum_{i=1}^{N-M} \beta_i (\alpha + f_i^{DL}) + 2\sum_{j=1}^{M} \kappa_j (\alpha + f_j^{DL}) \tag{2.8b}$$

the total transmitting power of BS *b* can be deduced from (2.4) and (2.7) and written as:

$$P_b = \frac{A}{1-\varphi-L} \tag{2.8}$$

When the number of mobiles in a cell increases, the parameter *L* increases too. Consequently the transmitting power of BS *b* increases. *L* represents the total load of the cell.

Remarks:

The authors of [4] assumed all links within the active set have the same transmit power. This condition is stronger than our statistical hypothesis (*M=P*). Furthermore, in [4] the authors consider another strong assumption: all the interference factors have the same value. We *consider the exact values* of this parameter: this one varies with the position of the mobile in the cell.

2.3 Macrodiversity load

Each mobile in the cell induces a specific load. To analyze the macrodiversity effect, we need to express that one considering mobiles either in macrodiversity or not. The cell's load *L* (2.8a) can be expressed as:

$$L = L_{DL} + L_{MD} \tag{2.9}$$

The first term:

$$L_{DL} = \sum_{i=1}^{N} \beta_i (\alpha + f_i^{DL}) \tag{2.10}$$

takes into account *all the mobiles* of the cell. It represents the cell's load, for the downlink, *in a case where there is no macrodiversity*. When a mobile is *not in macrodiversity,* we notice, from (2.4a), that $\Omega_i = 0$ and $\kappa_i = \beta_i$. Introducing:

$$\sigma_i = \frac{\Omega_i}{1 + \alpha\gamma_i} \tag{2.10a}$$

we can write:

$$\kappa_i = \beta_i \left(1 - \frac{\sigma_i}{1 + \sigma_i} \right) \tag{2.10b}$$

We can express:

$$L_{MD} = \sum_{j=1}^{M} \beta_j \left(\frac{1 - \sigma_j}{1 + \sigma_j}\right)(\alpha + f_j^{DL}) \tag{2.11}$$

This term represents an *extra load* due to the fact that *M* mobiles among *N are in macrodiversity*. Since $0 \le \sigma_j = \dfrac{\Omega_j}{1 + \alpha\gamma_j} \le 1$ (2.12), the load L_{MD} is positive.

Expressing the total transmitting power of a BS, our analysis explicitly shows the macrodiversity induces a specific positive load L_{MD} in the cell, increasing its total load. The consequence of this increase is to *decrease* the capacity (number of mobiles, throughput) of the cell. Considering the analytical expression of L_{MD}, our analysis moreover allows to *identify* the parameters which have an explicit influence on that macrodiversity *extra load*: The QoS characterized by β_i, the base stations transmitting powers (interference factor f_i^{DL}) and the term $\dfrac{1 - \sigma_j}{1 + \sigma_j}$ characterizes the powers received from the base stations with which a mobile is in macrodiversity. It appears interesting to calculate analytically this extra load. In this aim, we need to express analytically the parameters contributing to L_{MD}, and particularly the downlink interference factor f_i^{DL}. Hereafter we propose an analytical approach which allows to calculate L_{MD}.

3 Analytical fluid model

The key modelling step of the model we propose consists in replacing a given fixed finite number of transmitters (base stations or mobiles) by an equivalent continuum of transmitters which are distributed according to some distribution function. We denote it a fluid model [9] [11]. We consider a traffic characterised by a mobile density ρ_{MS} and a network by a base station density ρ_{BS}. For a homogeneous network, the downlink interference factor only depends on the distance *r* between the BS and the mobile. We denote it f_r. From [9] [11], we have:

$$f_r = \frac{\rho_{BS}.2\pi}{(\eta+2)r^{\eta}}.\left[(R-r)^{\eta+2} - \left(2R_c - r\right)^{\eta+2}\right] \tag{3.1}$$

3.1 Load model with macrodiversity

Using the analytical expression of the interference factor (3.1), and the expressions (2.9) (2.10) and (2.11), we aim to express hereafter the load L of the cell. The parameters γ_i β_i and κ_i , which characterize the QoS of the mobiles, depend on the service used by the mobile *i*. We assume that these parameters may also depend on the distance r of the mobile from its serving BS *b* and write them γ_r β_r κ_r. The parameters Ω_i and σ_i can be written Ω_r and σ_r. Considering that mobiles use one service we can drop the index *i*. In fact, the providers have the choice to modify the mobiles' QoS for them to be admitted in the cell. And this modification may depend on the position of the mobile. The expression of the total transmitting power of BS *b*, considering the mobiles located at distances *r* from the base station *b* is given by (2.8) .From (2.8a) and (2.8b), we have :

$$A = \sum_{r<R_{th}} N_r \beta_r \frac{Noise}{g_{b,r}} + 2\sum_{r\geq R_{th}} N_r \kappa_r \frac{Noise}{g_{b,r}} \tag{3.2}$$

and

$$L = \sum_{r<R_{th}} N_r \beta_r (\alpha + f_r^{DL}) + 2\sum_{r\geq R_{th}} N_r \kappa_r (\alpha + f_r^{DL}) \tag{3.3}$$

where N_r represents the number of mobiles located at a distance *r* from the BS *b*, R_{th} is a threshold distance defining the macrodiversity zone: If $r < R_{th}$ a mobile is not in macrodiversity, and he is in macrodiversity otherwise. We notice moreover that mobiles at a given distance *r* have the *same values* of interference factor f_r in our analytical model. Considering the network (base stations and mobiles) as a continuum of transmitters characterized by a base station density ρ_{BS} and a mobile density ρ_{MS}, we can replace the discrete summations (3.2) and (3.3) by continuous ones and express the load L with integrals. Considering a macrodiversity zone with *one* neighbor (figure 1, base stations *b* and *l*), the expression of the cell's load (3.3) can be rewritten as:

$$L = \int_{-\frac{\pi}{6}}^{+\frac{\pi}{6}} \int_0^{R_{th}} \rho\beta_r(\alpha + f_r).r.drd\theta + 2 \int_{-\frac{\pi}{6}}^{+\frac{\pi}{6}} \int_{R_{th}}^{R_c} \rho\kappa_r(\alpha + f_r).r.drd\theta \quad (3.4)$$

In a network, it is currently assumed that a cell *b* is surrounded by 6 cells (figure 1). Considering there is a macrodiversity zone with each one (figure 1) and assuming all the macrodiversity zones are identical (figure 1) (homogeneous network), we can write the loads expressions (2.10) and (2.11) as:

$$L_{DL} = 2.\pi \int_0^{R_c} \rho\beta_r(\alpha + f_r)r.dr \quad (3.5)$$

and

$$L_{MD} = 2.\pi \int_{R_{th}}^{R_c} \left(\frac{1-\sigma_r}{1+\sigma_r}\right) \rho\beta_r(\alpha + f_r)rdr \quad (3.6)$$

We showed (Section 2) that the analytical expression of L_{MD} enables to determine the parameters which have an influence on the extra load due to the macrodiversity: the QoS, the BS transmitting powers and the term $\left(\frac{1-\sigma_r}{1+\sigma_r}\right)$. Another parameter explicitly appears, highlighted by the fluid model: the macrodiversity size' zone characterized by R_{th}.

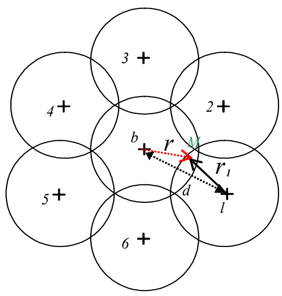


Fig. 1. Cell *b* sharing macrodiversity zones with its 6 neighbours

4 Admission control analysis

4.1 General Analysis

For the downlink, we express that the power of the base station P_b is limited to a maximum value $P_{\max}$: the call admission control is based on the probability P^{DL} to satisfy the following relation: $P^{DL} = \Pr[P_b > P_{\max}]$ which can be expressed, using (2.8):

$$P^{DL} = \Pr\left(L > 1 - \varphi - \frac{A}{P_{\max}} \right) \tag{4.1}$$

The cell load L is expressed by (2.9) (3.5) and (3.6). To analyze the admission control, we first need to calculate analytically the expressions (3.5) and (3.6) of L_{DL} and L_{MD}. In a general case, the QoS dependency with the position of the mobile (β_r) in the cell depends on the strategies of the provider: different strategies can be adopted, and for each one that dependency may be different. We will adopt a strategy where the QoS offered to the mobiles do not vary with the position of the mobiles ($\beta_r = \beta$, and $\sigma_r = \sigma$) and write from (3.5) and (3.6):

$$L_{DL} = 2\pi\rho\beta\int_0^{R_c} (\alpha + f_r) r dr \tag{4.2}$$

and

$$L_{MD} = 2\pi\rho\beta\int_{R_{th}}^{R_c} \left(\frac{1-\sigma}{1+\sigma} \right) (\alpha + f_r) r dr \tag{4.3}$$

We introduce the downlink average interference factor F_{DL} for the whole cell as:

$$F_{DL} = \frac{1}{S} \int_0^{R_c} \int_0^{2\pi} f_r \, r dr d\theta \tag{4.4a}$$

and

$$A_{DL} = \frac{1}{S} \int_0^{R_c} \int_0^{2\pi} r^{1-\eta} dr d\theta \tag{4.4b}$$

where S is the surface of the cell. We moreover introduce the parameter Considering $n^{MS} = \rho_{MS} \pi R_c^2$ mobiles in the cell, the expression (4.1) can thus be written:

$$P^{DL} = \Pr\left(n^{MS} > n_{DL}^{th} \right) \tag{4.5}$$

where:

$$n_{DL}^{th} = \frac{1-\varphi}{\beta(\alpha + F_{DL})} \tag{4.6}$$

and as long as long as the *Noise* is very low, i. e.:

$$\frac{A_{DL} Noise}{P_{\max}(\alpha + F_{DL})} << n_{DL}^{th} \tag{4.7}$$

The downlink interference factor analytical expression (3.1) takes into account the network's size. We denote $c_1 = \frac{2R_c}{R} = \frac{2R_c}{(2N_R + 1)R_c} = \frac{2}{2N_R + 1}$. This parameter represents the relative dimensions of the network compared to the distance between two localisations of BS. N_R represents the number of rings of cells around the studied one. Considering $\rho_{BS} = \dfrac{1}{\pi R_c^2}$, we obtain, from (4.4a) and (3.1):

$$F_{DL} = \frac{-2^{\eta+4}}{(2+\eta)} \int_0^1 x^{1-\eta} \left[\left(1-\frac{x}{2}\right)^{\eta+2} - c_1^{-2-\eta}(1-c_1\frac{x}{2})^{\eta+2} \right] .dx \tag{4.8}$$

and we notice that F_{DL} is positive due to $\eta < -2$. The expression of F_{DL} does not explicitly depend on the size of a cell, but only on its relative dimension to the network's one characterized by the parameter c_1. As we can observe (Table 1) the average interference factors are limited; they tend to an asymptotic value, when the network's dimension increases. For high size networks, *i.e.* $N_R \to \infty$, F_{DL} does no more depend on the network's size: $F_{DL} = \dfrac{-4}{(2+\eta)} \displaystyle\int_0^1 x^{1-\eta}(2-x)^{\eta+2} .dx$. As a consequence, for a homogeneous network the number of mobiles per cell *does not depend* on the size of the cell. It partially depends on the environment characterized by the pathloss factor η, the SIR target, the orthogonal factor α and the power ratio dedicated to the common channels φ.

4.2 Macro diversity impact

We introduce the downlink average interference factor for the macrodiversity zone:

$$F_{MD} = \frac{1}{S} \int_{R_{th}}^{R_c} \int_0^{2\pi} \left(\frac{1-\sigma}{1+\sigma} \right) f_r \, rdr.d\theta \tag{4.9a}$$

We moreover introduce the parameters:

$$\Gamma_{MD} = \frac{1}{S} \int_{R_{th}}^{R_c} \int_0^{2\pi} \left(\frac{1-\sigma}{1+\sigma} \right) \alpha rdr.d\theta \tag{4.9b}$$

and

$$A_{MD} = \frac{1}{S} \int_{R_{th}}^{R_c} \int_0^{2\pi} r^{1-\eta} drd\theta \tag{4.9c}$$

We can write (4.1) as:

$$P^{DL} = \Pr\left(n^{MS} > n^{th}\right) \tag{4.10}$$

where:

$$n^{th} = \frac{1-\varphi}{\beta(\alpha + F_{DL} + F_{MD} + \Gamma_{MD})} \tag{4.11}$$

and as long as long as the *Noise* is very low, i.e.:

$$\frac{(A_{DL}+A_{MD})Noise}{P_{\max}(\alpha+F_{DL}+F_{MD}+\Gamma_{MD})} << n^{th} \tag{4.12}$$

The macrodiversity consequence is to decrease the term n^{th} which represents the limit capacity of the cell.

5 Macrodiversity generalization

For the downlink, we express that the useful power received by a mobile belonging to the base station *b* comes from N_{MD} base stations of the network. Considering that any mobile is in macrodiversity with *all the base stations* of the network, $N_{MD} = N_{BS}$, the expression (2.1) is thus rewritten as:

$$\frac{P_{ib}g_{ib}+\sum_{l\neq b}^{N_{BS}}P_{il}g_{il}}{\alpha(P_b-P_{ib})g_{ib}+\sum_{l\neq b}^{N_{BS}}(P_l-P_{il})g_{il}+N_{th}} \geq \gamma \tag{5.1}$$

Where P_{il} is the useful transmitting power coming from the base station l towards the mobile *i* belonging to the base station *b*, and g_{il} is the path loss between the base station *l* and the mobile *i*, P_l is the total transmitting power of the base station *l*

$$P_{ib}g_{ib}+\sum_{l\neq b}^{N_{BS}}P_{il}g_{il}=\gamma\left(\alpha(P_b-P_{ib})g_{ib}+\sum_{l\neq b}^{N_{BS}}(P_l-P_{il})g_{il}+N_{th}\right) \tag{5.2}$$

Denoting:

$$\mu=\frac{1+\gamma}{1+\alpha\gamma} \tag{5.2b}$$

(we drop the indexes *i* and *DL*), we can write:

$$P_{ib}=\beta(\alpha P_b+f_iP_b+N_{th}/g_{ib})-\mu\frac{1}{g_{ib}}\sum_{l\neq b}^{N_{BS}}P_{il}g_{il} \tag{5.3}$$

In our analysis, each base station of the network contributes to the useful power received by any mobile belonging to any base station. Due to the fact that the base stations transmitting powers are limited, and that the mobiles number in the network is great, it is reasonable to consider a limitation of the available transmitting powers P_{il} dedicated to the macrodiversity. Moreover, considering the great distances between the other base stations of the network and the mobile i belonging to the base station b, we can assume that the base stations use the maximum power (denoted P) available for the transmitting power P_{il} We notice an analogy with the expression (2.2): we can write, when all the base stations transmitting powers are identical: $P_l=P_b$ for $l = 1 \ldots N_{BS}$, and when all the transmitting powers P_{il} equal P:

$$\frac{1}{g_{ib}}\sum_{l\neq b}^{N_{BS}} P_{il}\, g_{il} = P\frac{1}{g_{ib}}\sum_{l\neq b}^{N_{BS}} g_{il} = Pf_i \tag{5.4}$$

These last assumptions can be verified if the network is homogeneous, or when base stations manage a maximum number of mobiles. The total transmitting power of BS b can thus be written as:

$$P_b = \sum_{i=1}^{N} P_{ib} + \sum_{j\neq b}^{N_{BS}}\sum_{i=1}^{N} P + P_{CCH} \tag{5.5a}$$

or

$$P_b = \sum_{i=1}^{N} P_{ib} + N(N_{BS}-1)P + P_{CCH} \tag{5.5b}$$

and finally:

$$\sum_{i=1}^{N} P_{ib} = \sum_{i=1}^{N} \beta(\alpha P_b + f_i P_b + N_{th}/g_{ib}) - \mu\sum_{i=1}^{N} Pf_i \tag{5.6a}$$

Considering that the power P is a fraction of the total power P_b, we can write, $P=\varepsilon P_b$., and when:

$$P_{cch}=\varphi P_b \quad \sum_{i=1}^{N} P_{ib} = N\beta\alpha P_b + (\beta-\mu\varepsilon)P_b\sum_{i=1}^{N} f_i + \sum_{i=1}^{N} \beta N_{th}/g_{ib} \tag{5.6b}$$

and $$P_b = N\beta\alpha P_b + (\beta-\mu\varepsilon)P_b\sum_{i=1}^{N} f_i + \sum_{i=1}^{N} \beta N_{th}/g_{ib} + N(N_{BS}-1)\varepsilon P_b + \varphi P_b$$

So we have:

$$P_b\left(1-\varphi-N\beta\alpha-(\beta-\mu\varepsilon)\sum_{i=1}^{N} f_i - N(N_{BS}-1)\varepsilon\right) = \sum_{i=1}^{N} \beta N_{th}/g_{ib} \tag{5.6c}$$

Using our analytical model we can write: $\sum_{i=1}^{N} f_i$ as $\int_0^{R_c}\int_0^{2\pi} \rho_{MS} f_r \, rdrd\theta$

Denoting:

$$F = \frac{1}{S_{cell} S_{Network}} \int_0^{R_c} \int_0^{2\pi} \frac{2\pi}{(\eta+2)r^{\eta}} \cdot \left[(R-r)^{\eta+2} - (2R_c - r)^{\eta+2} \right] r dr d\theta \tag{5.7}$$

we can write $P_b \left(1-\varphi - N_{MS}\beta\alpha - (\beta-\mu\varepsilon) N_{MS} N_{BS} F - N_{MS}(N_{BS}-1)\varepsilon\right) = \sum_{i=1}^{N} \beta N_{th}/g_{ib}$ and express P_b as:

$$P_b = \frac{\sum_{i=1}^{N} \beta N_{th}/g_{ib}}{1-\varphi - N_{MS}\left(\beta\alpha - (\beta-\mu\varepsilon) N_{BS} F - (N_{BS}-1)\varepsilon\right)} \tag{5.8}$$

The denominator has to be positive:
$1-\varphi - N_{MS}\left(\beta\alpha - (\beta-\mu\varepsilon) N_{BS} F - (N_{BS}-1)\varepsilon\right) > 0$

So the cell capacity is given by:

$$N_{MS} = \frac{1-\varphi}{\beta\alpha + (\beta-\mu\varepsilon) N_{BS} F + (N_{BS}-1)\varepsilon} \tag{5.9}$$

We denote $N_{1,MS}$ the cell capacity without macrodiversity**,** *i.e.* $\varepsilon=0$:

$$N_{1,MS} = \frac{1-\varphi}{\beta\alpha + \beta N_{BS} F} \tag{5.10}$$

Does the macrodiversity increase the capacity of a cell? To answer that question we compare (4.9) and (4.10):

$\frac{1-\varphi}{\beta\alpha + (\beta-\mu\varepsilon) N_{BS} F + (N_{BS}-1)\varepsilon} > \frac{1-\varphi}{\beta\alpha + \beta N_{BS} F}$ which can be written as $\beta\alpha + (\beta-\mu\varepsilon) N_{BS} F + (N_{BS}-1)\varepsilon < \beta\alpha + \beta N_{BS} F$ and finally, denoting

$$N_{BS,th} = \frac{1}{1-\mu F} \tag{5.11}$$

we conclude that macrodiversity increases the capacity only if we have:

$$N_{BS} < N_{BS,th} \tag{5.12}$$

For $\eta=-3$, $R_c = 1$, $R = 10$, we obtain F= 0.72% .

For α=0.7 and γ=-16dBm (voice service), we have $N_{BS,th} = 1.007$. The downlink macrodiversity *decreases* the capacity of a cell. We can observe that result whatever the values of F. The loss of capacity due to macrodiversity is Loss = N_{1MS}-N_{MS}

$$\text{Loss} = \frac{1-\varphi}{\beta\alpha + \beta N_{BS} F} - \frac{1-\varphi}{\beta\alpha + (\beta - \mu\varepsilon) N_{BS} F + (N_{BS} - 1)\varepsilon}$$

$$= (1-\varphi)\frac{(-\mu\varepsilon) N_{BS} F + (N_{BS} - 1)\varepsilon}{(\beta\alpha + \beta N_{BS} F)(\beta\alpha + (\beta - \mu\varepsilon) N_{BS} F + (N_{BS} - 1)\varepsilon)}$$

Figures 2 and 3 show the loss of capacity in term of mobile number (figure 2: orange curve) and loss percentage of cell capacity (figure3: violet curve) as a function of the percentage of power ε dedicated to each link for the macrodiversity. The red curve shows the total transmitting power of a base station, dedicated to mobiles in macrodiversity.

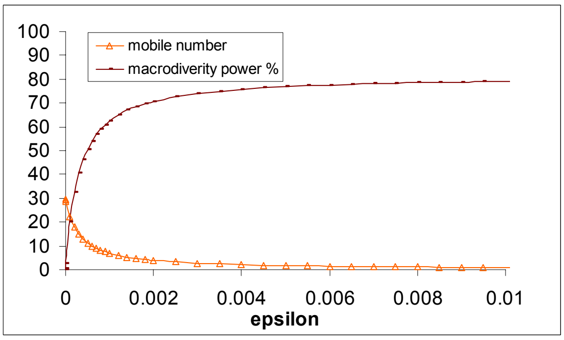


Fig. 2. Macrodiversity impact on the cell capacity vs percentage of transmitting power

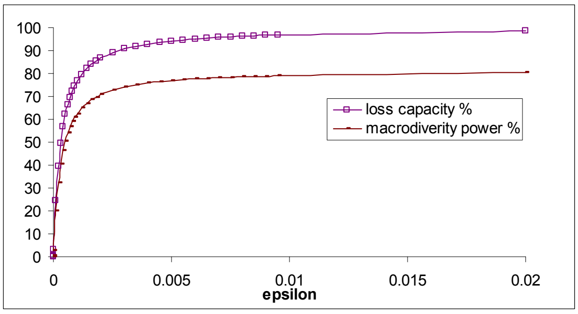


Fig. 3. Macrodiversity impact on the loss of capacity vs percentage of transmitting power

Cancellation of the other cell interferences

We notice from (4.6b) that the term f_i vanishes for $\beta=\mu\varepsilon$, as if the interferences felt by a mobile, due to the other base stations of the network, were *balanced* by the fraction of their transmitting powers dedicated to that mobile. Since

$\beta = \dfrac{\gamma}{1+\alpha\gamma}$ and $\mu = \dfrac{1+\gamma}{1+\alpha\gamma}$, we have $\varepsilon = \dfrac{\gamma}{1+\gamma}$ The cell capacity $N_{1,MS}$ can be written:

$$N_{1,MS} = \frac{1-\varphi}{\beta\alpha} \tag{5.13}$$

6 Conclusion

In this paper, we established an explicit expression of the load L_{MD} due to mobiles in macrodiversity, and showed that one increases the cell's load. We identified the traffic and network's parameters which play a key role in the cell's load. We finally generalized the approach, considering a macrodiversity with a great number of base stations. Though mainly focused on CDMA networks, our analysis can be applied to any frequency reuse 1 network based on other technologies, such as OFDMA.

References

1. A. J. Viterbi, CDMA Principles of Spread Spectrum Communication, Wesley, 1995.
2. T. Bonald and A. Proutiere, Wireless Downlink Data Channels: User Performance and Cell Dimensioning, ACM Mobicom 2003
3. Jaana Laiho, Achim Wacker Tomas Novosad, "Radio network planning and optimisation for UMTS"
4. Hiltunen, K., De Bernardi, R. WCDMA Downlink capacity estimation, VTC 2000, p. 992-996
5. F. Baccelli, B. Błaszczyszyn, and F. Tournois (2003) Downlink admission/congestion control and maximal load in CDMA networks, in Proc. of IEEE INFOCOM'03
6. H. Holma A. Toskala, WCDMA for UMTS, Radio Access for Third Generation Mobile Communications. John Wiley & Sons, Ltd.,2001.
7. S.V Hanly,., "Capacity and Power Control in Spread Spectrum Macrodiversity Radio Networks", IEEE Trans. on Comm., vol. 44, NO. 2, pp.247-256, Feb. 1996
8. D. Aktas, M. N. Bacha, J. S. Evans, and S. V. Hanly, Scaling Results on the Sum Capacity of Cellular Networks With MIMO Links, IEEE transactions on information theory, vol 52, n°7, July 2006
9. J-Marc Kelif and E. Altman, Downlink fluid model for CDMA Networks, VTC 2005 Stockholm
10. P. Jacquet, "Geometry of information propagation in massively dense adhoc networks," in Proc. ACM MobiHOC, Roppongi Hills, Japan, May 2004, pp. 157–162.
11. J-Marc Kelif, M. Coupechoux, and P. Godlewski, Spatial Outage Probability for Cellular Networks, Globecom 2007, Washington

Multiple Cell Partitions for Increasing the CDMA-Based Cell Capacity

Ardian Ulvan[1] , Diogo Ribeiro[2] and Robert Bestak[1]

[1]Czech Technical University in Prague, Technicka 2 166 27, Praha 6, Czech Republic
ulvana1, bestar1[@fel.cvut.cz]

[2]Instituto Superior Técnico de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
dpbr@mega.ist.utl.pt

Abstract. This paper investigates the impact of cell partitioning in cell capacity of CDMA-based system. We examine the implementation of four partitions per cell as well as the influence of various height of the base station transceiver antenna to the system. We contemplated the urban area as the target, therefore the COST-231 Walfisch – Ikegami is applied as the propagation model. Calculations on the capacity of cell, the link budget (and MAPL) and the radius of each partition, depending on the height of the base station transceiver antenna, are made. The results show that the capacity increases as the number of partitions increases; the height of the base station transceiver affects the radius of the partitions.

1 Introduction

The conventional method for cellular planning is based on multi-cell configuration. The topology has a base transceiver station (BTS) that serves areas divided in cells or several BTS covering the whole area. However, in this method, to avoid the co-channel interference, each adjacent cell needs to use different frequencies. In practice, the spacing has to be more than just adjacent cells, around 7 frequencies are often used per planning. Thus, to increase the capacity, the number of frequency channels would have to be increased. Since frequency is a precious resource and in most cities the growth of traffic tends to concentrate in certain area only, this method becomes very inefficient.

The use of CDMA-based systems in this work is due to its potential concerning capacity increase and frequency spectrum management. However, since this type of systems are strongly influenced by interference between users or even the one that comes from base transceiver stations, the way to improve capacity is to control this sources of interference. These two types are called inter-user interference and co-channel interference. This paper describes the use of cell partition as an alternative solution for CDMA-based cellular planning.

In this paper we analyze the effect of increasing the number of partitions and varying the BTS's antenna height.

Resorting to a variable number of partitions, an existing cell is divided into 4 partitions, being scaled in radius as well as in frequency. In order to determine the radius of each partition, it's required the calculation of link budget, which provides the maximum allowable path loss (MAPL) and the usage of a propagation model, which is in this case the Walfisch – Ikegami. After having all of this data, it's possible to determine the maximum capacity of the cell.

The paper is organized as follows: the definition of the cell partition for improving cell capacity, frequency planning and channel allocation scheme for partitioned cell, link budget and cell radius calculations are discussed in Section II. Section III proposes three and four partitions topology in each cell that are used in or simulation scenarios. In Section IV we discussed the results of total capacity of the system and compared them with the capacity of conventional frequency planning. Finally, section V and VI concludes the work and assign our future work.

2 Cell Capacity

2.1 Variable number of partitions

Increasing the cell capacity by using 2-partition topology was carried out by [1]. However, the used of two different frequencies for inner and outer cell seems have low complexity in term of interference. Additionally, the cell radius which is influenced by antenna altitude was not considered yet. This paper intends to determine the complexity by increase the number of partitions and analyze what happens to the total capacity of the cell. A cell is divided into four partitions, all of them with a radius disparity that is scaled between them. The way to perform the scaling of radius is to vary the height of the antennas and the transmitting power of each BTS [5]. So, the scheme of one cell is shown in figure 1.a below.

If this cell is spanned throughout a whole coverage area, the frequencies within each partition have to be alternated, and so, for a 3 and 4 partitions scheme, we have a frequency planning for each partitions as can be seen on figure 1.b.

Note that in this figure each colour corresponds to one different frequency, so the goal of not having boundaries with common frequencies on each side is achieved.

The frequency planning is the key to improve the capacity of the system. Each partition within the cell, have a different frequency not to cause interference between the partitions. It means that with three partitions we have a frequency reuse factor of three, with four partitions, a reuse factor of four, and so on. To maximize the capacity of each cell, one has to minimize the interference, since CDMA is an interference limited technology. When a mobile station moves to the cell's boundary, the interference from neighboring cells increase considerably. The worst case for the forward link occurs at the boundary of three cells where powers received from two adjacent cells are almost equal to that from the given cell. Taking this fact into consideration, the goal of the frequency planning is to avoid the existence of cell boundaries with the same frequency in each of the outer partitions that compose this boundary, which yield the distribution in figure 1.b for a 3 cell partition scheme, and in figure 1.c for a 4 cell partition topology.

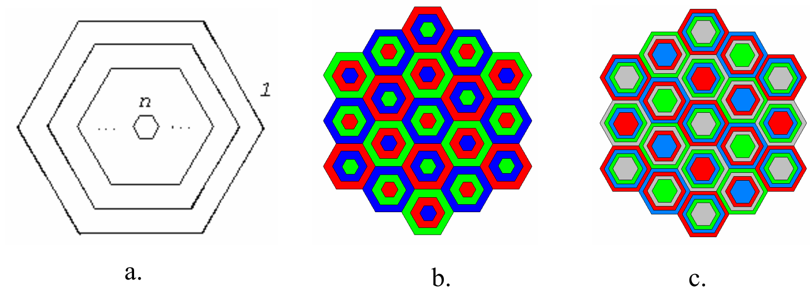


Fig.1. Schematic representation of a cell containing n partitions (a) and frequency planning for a scheme with 3 and 4 partitions per cell (b, c)

Accordingly as it is mentioned, each partition is designed to use different frequencies. The outer most partition always includes the coverage of the other ones, consequently there are as many frequencies as the number of partitions in the outer most cell. However, there is no interference since all of the frequencies are different.

Concerning the traffic allocation process it becomes slightly different from the one without partitions. The traffic allocation process is always prioritised to the inner most cell. If a mobile station (MS) is in the inner most cell coverage, the allocation of channel is served by its frequency and the connection is held by the inner most cell's radio base station (RBS). On the other hand, if there are no idle channels in the inner most cells, the connection is relocated to the next partition (the second smallest in radius) and the system tries to establish the connection here. If it is not possible as well, the system tries the next partitions in an orderly fashion from the smallest to the biggest radius partition, until the connection is established or rejected. The rejection can be due to all of the radio base stations not having idle traffic channels or the mobile station moved farther away than the radius of the outer most cells. When the connection is established, it is served by the frequency of the partition where an idle channel has been found. In figure 2, it is shown the algorithm of traffic channel allocation in a cell with an indefinite number of partitions.

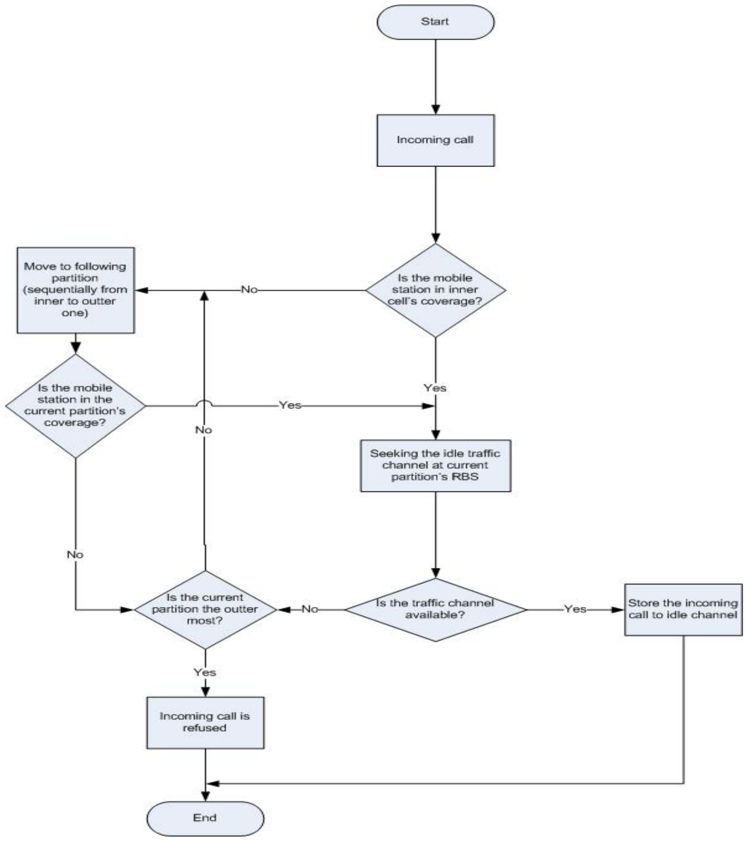


Fig. 2. Channel allocation algorithm for an indefinite number of partitions

2.2 CDMA Considerations

In CDMA systems the W^{64} of Walsh code generates 1 pilot channel, 1 synchronization channel, 7 paging channels and 55 traffic channels. To allow enough bandwidth for data and for bandguard, the 55 traffic channels can be served by 1.25 MHz of bandwidth. The capacity of the system, which is represented by the number of users that the system can support, with a single cell topology is [6]:

$$N = 1 + \frac{W / R}{E_b / N_0} - (\eta / S) \tag{1}$$

In above equation it was considered the background thermal noise, η, which has to be taken into account in the spread bandwidth.

2.3 Link Budget

To determine the radius, it needs to be known the *link budget,* this allows the calculation of the total losses and gains on the transmission link. It is known that the signal in receiver can be detected if the following condition is reached [5]:

$$\left(P_{tr}\right)_{dBm} + (Gains)_{dB} - (Losses)_{dB} > (\textit{Min. required power for detection at the receiver})_{\mathrm{dBm}}$$

The result of the link budget calculation is a cell's *MAPL* (Maximum Allowable Path Loss). This calculation is employed in both directions: the *reverse link* and the *forward link*. The *MAPL* for reverse and forward link is described in the following equations, respectively [2]:

$$\begin{aligned} MAPL_R = {} & \textit{Total mobile transmitter EIRP (dBm) - Receiver} \\ & \textit{sensitivity (dBm) + Rx Antenna Gain (dBi) - Rx Cable Loss } (dB) \\ & - \textit{Body Loss (dB) - Fade Margin (dB) - Building Penetration} \\ & \textit{Loss (dB) + Diversity Gain (dB)} \end{aligned}$$

$$\begin{aligned} MAPL_F = {} & \textit{Total mobile transmitter EIRP (dBm) - Receiver} \\ & \textit{sensitivity (dBm) + Rx Antenna Gain (dBi) - Rx Cable Loss } (dB) \\ & - \textit{Body Loss (dB) - Fade Margin (dB) - Building Penetration} \\ & \textit{Loss (dB)} \end{aligned}$$

The results attained for the link budget calculations are as follow.

Table 1. Results of Link Budget Calculation for a cell with three partitions.

	Unit	Outer Cell	Medium Cell	Inner Cell
BTS's Maximum transmitting power	dBm	35.00	30.00	25.00
MAPL	dB	133.81	128.81	123.8

Table 2. Results of Link Budget Calculation for a cell with four partitions

	Unit	Outer Cell	2nd tier Cell	3rd tier Cell	Inner Cell
BTS's Maximum transmitting power	dBm	40.00	35.00	30.00	25.00
MAPL	dB	138.81	133.81	128.81	123.81

2.4 Cell Partition's radius

By using the MAPL, it is possible to calculate the radius of a desired cell/partition using propagation models that are adequate for the environment where the cells/partitions are inserted. We consider the COST 231 propagation model, suitable for urban and dense urban areas.

To determine the cell radius, accurate data of the street and building altitude is required. The cell radius is assumed to be less than 5 km and the antenna elevation less than 70m and more than the average building height. The model employed here consists in several equations with restriction and conditions that are to be used combined. So, mathematical descriptions of the model are [3] [4]:

$$L = L_0 + L_{rts} + L_{msd} \tag{2}$$

note:

L = path loss (dB), L_0=free space loss (dB), L_{rts} = roof-top-street diffraction and scatter loss, L_{msd} = multi-screen diffraction loss.

$$L_0 = 32,4 + 20.\log(r) + 20.\log(f) \tag{3}$$

$$L_{rts} = -16,9 - 10.\log(w) + 10.\log(f) + 20.\log(\Delta_{mobile}) + L_{street} \tag{4}$$

$$for\ \Delta_{mobile} > 0$$

$$L_{rts} = 0 \quad for\ \Delta_{mobile} \leq 0 \tag{5}$$

$$L_{street} = -10 + 0,354\phi \quad for\ 0 \leq \phi < 35 \tag{6}$$

$$L_{street} = 2,5 + 0,075(\phi - 35) \quad for\ 35 \leq \phi < 55 \tag{7}$$

$$L_{street} = 4,0 - 0,114(\phi - 55) \quad for\ 55 \le \phi \le 90 \tag{8}$$

note:

h_{roof}= average of roof building altitude (m), h_{mobile}=antenna altitude for MS(m), h_{BTS}= antenna altitude for BTS(m), Δ_{mobile}=h_{roof} h_{mobile} (m), Δ_{BTS}=h_{BTS}-h_{roof} (m), w= average of street width (m), ϕ= road orientation concerning to direct radio path (degree).

$$L_{msd} = L_{med} + k_a + k_r \log(r) + k_f \log(f) - 9\log(b) \tag{9}$$

where:

$$L_{med} = -18\log(1 + \Delta_{BTS}) \quad for \Delta_{BTS} > 0 \tag{10}$$

$$L_{med} = 0 \qquad for \quad \Delta_{BTS} \le 0 \tag{11}$$

$$k_a = 54 \qquad for \quad \Delta_{BTS} > 0 \tag{12}$$

$$k_a = 54 - 0,8\Delta_{BTS}\ for\ r \ge 0,5\ and\ \Delta_{BTS} \le 0 \tag{13}$$

$$k_a = 54 - 1,6\Delta_{BTS} r\ for\ r < 0,5 and \Delta_{BTS} \le 0 \tag{14}$$

$$k_r = 18 \quad for \quad \Delta_{BTS} > 0 \tag{15}$$

$$k_r = 18 - 15\frac{\Delta_{BTS}}{h_{roof}} \quad for \quad \Delta_{BTS} \le 0 \tag{16}$$

$$k_f = -4 + 0,7\left(\frac{f}{925} - 1\right) \tag{17}$$

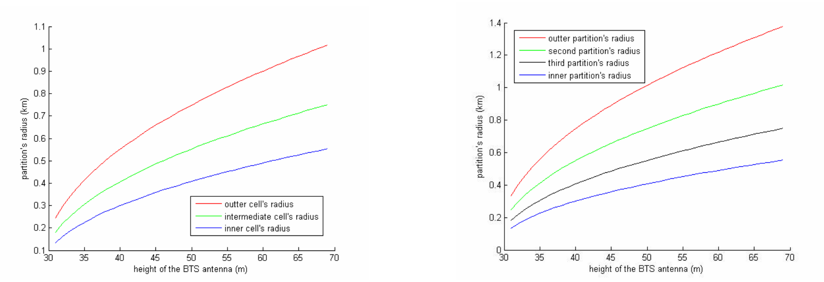
for urban and suburban area

$$k_f = -4 + 1,5\left(\frac{f}{925} - 1\right) \tag{18}$$

for dense urban area

note:
b is the average interbuilding distance (m), k_a and k_r are the correction constants of antenna altitude, kf is the adaptation constant for diverse building density.

In this paper, the height of the BTS antenna will be varied, so the results for the radiuses will be dependent of it. In figure 3.a and 3.b, the results of the calculations are explicit for a 3 and 4 partitions scheme, respectively:



a. b.

Fig. 3. Variation of the several partitions' radiuses with the height of the BTS antenna for 3 (a) and 4-partitions topology (b).

3 Cell Capacity with 3 and 4 Partitions Topology

The equation (1) allows the calculation for the capacity in a single-cell scheme. With a multipartitional topology per cell some other considerations have to be taken into account. However, when the cell partition is done, a different frequency is used for each of the resulting cells and since they do not interfere with one another, it's possible to calculate the capacity individually for each of these. Afterwards, all of the capacities are summed to yield the final result. So, the total capacity of the cell with the partitions is be given by:

$$N_{total} = \sum_{i=1}^{n} N_i \tag{19}$$

where N_{total} is the total capacity of the cell with the partitions and N_i is the capacity of the i^{th} partition. Due to this separation principle, for an arbitrary partition of the cell, the S/I ratio is given as:

$$SNR = \frac{P_t \cdot (1/N) \cdot r^{-\alpha}}{P_t \cdot \left(1 - \frac{1}{N}\right) \cdot r^{-\alpha} + \sum_{k=1}^{3} \sum_{j=1}^{6} P_{kj} \cdot L_{kj}^{-\alpha}} \tag{20}$$

then

$$N_i = \frac{P_i \cdot r_i^{-\alpha} \cdot \left(1 + \frac{S}{I}\right)}{\frac{S}{I} \cdot \left(P_i \cdot r_i^{-\alpha} + \sum_{k=1}^{3} \sum_{j=1}^{6} P_{kj} L_{kj}^{-\alpha}\right)} \tag{21}$$

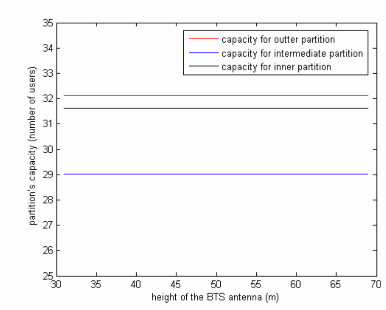
where

$$\frac{S}{I} = \frac{E_b / I_0}{W / R} = \frac{E_b / I_0}{G_P} \tag{22}$$

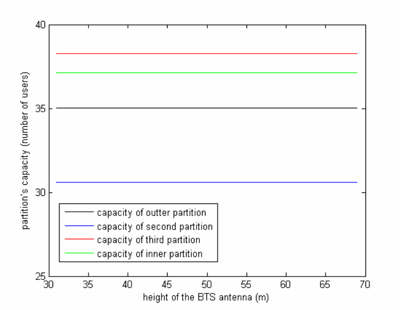
In the above equations S/I is the signal to interference ratio, P_i is the transmitted EIRP of the partition (Watt), r_i is the radius of the partition (km), P_{kj} is the transmitted power of neighbour cells (Watt), L_{kj} is the distance between neighbour base station to MS (km), α is the path loss exponent and N_i is the i^{th} partition capacity (number of users).

4 Results for the Traffic Capacity

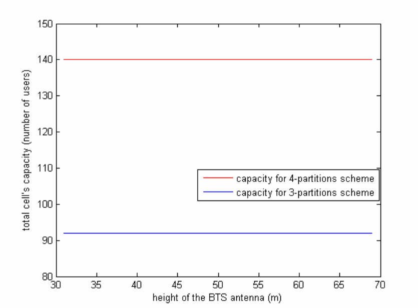
Using all of the mentioned equations, the results from the link budget calculation and the radiuses for each partition, are dependent of the height of each BTS. It is now possible to determine the total capacity of the system. This capacity is calculated for 3 and 4 partitions and depends on the BTS's antenna height. Figures 4.a and 4.b show the results of the capacity per partition per cell. In figure 4.c we can see the total capacity of the resulting cell. Tables 3 and 4 are the results for the capacity attained when using the conventional method and 2 partitions per cell topology.



a.



b.



c.

Fig. 4. Capacity of each partition depending on the height of the BTS antenna for 3-partitions scheme (a), 4-partitions scheme (b) and total cell's capacity for a topology with 3 and 4 partitions per cell.

Table 3. Results for calculation and simulation of capacity using conventional method (2 frequencies).

	Unit	RBS 1	RBS 2
BTS's EIRP	dBm	45	45
Frequency	MHz	1967.50	1966.25
Antenna altitude	m	50	50
MAPL	dBm	130.8	130.8
Cell radius	Km	0.75	0.75
Traffic capacity	users	29	29

Table 4. Results for calculation and simulation of capacity using a topology with 2 partitions per cell.

	Unit	Inner cell	Outer cell
BTS's EIRP	dBm	34	45
Frequency	MHz	1967.50	1966.25
Antenna altitude	m	40	50
MAPL	dBm	123.8	130.8
Cell radius	Km	0.36	0.75
Traffic capacity	users	45	35

5 Conclusions

Obtained results show that the cell capacity can be increased by using cell partitions. Furthermore, the capacity is increased linearly with the number of partitions used per cell. In case of 3 partitions the total cell capacity is increased to 92 users; and in case of 4 partitions per cell it is increased to 140 users. Using the conventional method, the capacity is only 58 users per cell and with 2 partitions per cell 80 users. The CDMA-based systems are indeed interference dependent. It implies that the only parameter affecting the capacity is the interference among users or caused by another BTS which is emitting using the same frequency. Concerning the capacity for each partition inside the cell, simulation results show that the inner cell has a very high capacity comparatively to the others.

The increase in the number of partitions has also the great advantage of allowing an effective frequency planning, since more frequencies are allowed to be used, and one can choose in which partition the capacity is to be increased.

6 Further Work

As discussed, the increase of the number of partitions increases the capacity in CDMA-based systems. However, increasing the number of partitions brings some drawbacks. The use of n-frequencies per cell, corresponding to n-partitions per cell, will lead to hard-handoff when the mobile station is leaving the coverage area from inside to outside of the cell. The hard handoff can lead to a degradation of the quality of service as well as the grade of service, which are two very important parameters that specify the minimum conditions for an acceptable conversation.

Acknowledgement

This research work was supported by grant of Czech Ministry of Education, Youth and Sports No. MSM6840770014.

References

1. Ulvan, A (2006) Increasing the CDMA-based Cell Capacity for Urban Area With Cell Partition. In Research in Telecommunication Technology. Proceeding, Vol.1, pp 176 – 181. ISBN 80-8070-637-9.
2. Kim, W. S. and Prabhu, V. K (1998) Enhanced Capacity in CDMA System with Alternate Frequency Planning. IEEE International Conference on Communication. Vol. 2, pp 972-978. ISBN 0-7803-4788-9.
3. Hecker, A., Neuland, M. and Kuerner, T. (2006) Propagation models for high sites in urban areas. Advance in Radio Science, Vol 4, pp 345-349.
4. Hecker, A., and Kuerner, T. (2005) Analysis of Propagation Models for UMTS Ultra High Sites in Urban Area. IEEE 16th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Vol 4, pp 2337 – 2341. ISBN 9783800729098.
5. Rappaport, T. S. (1996) Wireless communications principles and pratice", Prentice Hall PTR.
6. Ericsson Academy (2006) CDMA2000 RF Engineering Workshop.