

CCAP: CDMA Capacity Allocation and Planning

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Table of Contents

Table of Contents.....	1
1.0 Introduction.....	3
1.1 CDMA Characteristics	3
1.2 CDMA Capacity	4
1.3 CDMA Power Compensation Factor.....	4
2.0 CCAP	6
2.1 What is CCAP.....	6
2.2 CCAP Characteristics.....	6
2.3 CCAP Development History.....	8
2.4 Parameters and Functions.....	8
2.4.1 Base Station Database	8
2.4.2 Calculation of Area of Service	9
2.4.3 Calculation of Inter-Cell Interference	9
2.4.4 Calculation of Capacity	10
2.4.5 Calculation of Subscriber Performance	10
2.4.6 Calculating the Power Compensation Factor	11
2.4.7 CCAP Report	11
3.0 Algorithms and Equations.....	12
3.1 Hata Model	12
3.2 PCS Extension to Hata Model.....	13
3.3 Single Cell Reception – Hard Handoff	14
3.4 Access Outage – Single Cell and Perfect Power Control.....	15

3.5 Access Outage – Multiple Cell and Imperfect Power Control.....	17
3.6 Soft Handoff Reception.....	18
3.7 Rayleigh Fading.....	20
3.8 Optimization of Power Compensation Factor	22
3.9 Subscriber Capacity.....	22
3.10 Software Flow Chart.....	23
4.0 Test Results and Demos	26

1.0 Introduction

1.1 CDMA Characteristics

Code Division Multiple Access (CDMA) relies on the use of spread spectrum techniques to achieve multiple communication channels in a designated segment of the electromagnetic spectrum. With CDMA, each user's narrowband signal is modulated by a high rate special code (pseudo-random binary sequence). This causes the spreading of the bandwidth of the user's signal resulting in a wideband signal. A large number of CDMA users share the same frequency spectrum. If CDMA is viewed in either time or frequency domain, the signals appear to be overlapping; they are separated by their special code. In the receivers, the signals are correlated by the appropriate pseudo-random code which despreads the spectrum. The other users' signals whose codes do not match are not despread and therefore only appear as noise and represent a self-interference generated by the system. The signal-to-interference ratio for CDMA is determined by the ratio of the desired signal power to the total interference power from all the other users. The capacity of CDMA is therefore only limited by the amount of interference that can be tolerated from other users. This is why the capacity of CDMA is said to be interference limited (unlike FDMA and TDMA capacities which are primarily bandwidth limited).

Rapid, precise power control is a key requirement of CDMA technology. Although implemented to solve the near-far problem, this approach reduces power consumption by transmitting the minimum power required to maintain high voice quality. Transmitting less power means that a simpler and lower cost power amplifier can be employed in the design of portables. It also translates into a smaller portable unit with more talk time and standby time. The requirement for power control also imposes stringent requirements on the system, and the system performance, as this document will confirm, is very sensitive to the efficiency of the power control.

1.2 CDMA Capacity

CDMA cellular systems typically employ universal frequency reuse, where the bandwidth is shared by all the cells and transmissions are distinguished through the assignment of unique spreading sequences. For such systems, multiple access interference from neighboring cells must be carefully accounted for.

With cellular CDMA systems, any technique that reduces multiple access interference translates into a capacity gain. Since cellular CDMA systems use speech coding, the multiple access interference can be reduced by using voice activity detection along with variable rate speech transmission. This technique reduces the rate of the speech coder when silent periods are detected in the speech waveform. Voice activity detection has often been cited as an advantage of CDMA systems over TDMA systems.

Cell sectoring is another very effective method for reducing multiple access interference, where each cell is sectorized by using directional antennas. 120° cell sectoring reduces the multiple access interference by roughly a factor of three (on average).

1.3 CDMA Power Compensation Factor

As mentioned previously, power control is one of the most important system requirements of the CDMA system. At call setup the user compares the pilot signal of different base stations and locks onto the base station from which it receives the maximum pilot power. From then on until a hand-off occurs, the user will be associated with and power controlled by that base station.

Consider a network with a large cell I adjacent to a small cell J as shown in Figure 1. User A at the boundary of the large cell cause a lot of interference to user B at the boundary of the small cell. This is because users transmit power proportional to distance raised to the path loss exponent. Thus a small cell adjacent to a large cell will experience a great deal of interference.

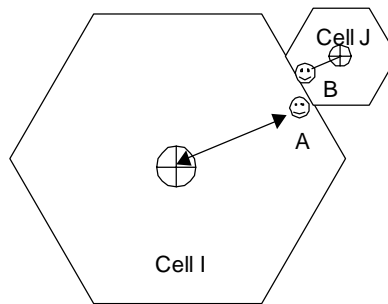


Figure 1

Since the capacity of CDMA is interference limited, this phenomenon causes a significant reduction in the capacity of the small cells. In order to alleviate this problem we propose to increase the nominal power of the users in the small cells by a factor we call the Power Compensation Factor (PCF). CCAP will find the optimal PCF that will maximize the capacity of the network

2.0 CCAP

2.1 What is CCAP

CCAP stands for CDMA Capacity Allocation and Planning. It is a graphical interactive tool for analyzing the capacity of a CDMA (Code Division Multiple Access) network and optimizing that capacity. For a given network, the program first calculates the area of coverage. It does so by using the HATA COST 231 propagation model. Other models can be incorporated and used appropriately. Once the area of coverage is defined, it accurately calculates the call capacity of the network. It finds the inter cell interference and the intra cell interference and using a given blocking probability the current capacity is found. It then optimizes this capacity by finding the appropriate Power Compensation Factor (PCF) and fine tuning the reverse power of the mobiles. Once the optimal PCF's are found, the new optimal capacity is calculated. Finally it calculates the subscriber performance of each cell and of the entire network.

2.2 CCAP Characteristics

CCAP is a very versatile tool. It incorporates all the features that distinguish CDMA from other current PCS solutions. Some of the features of CCAP include:

Capacity calculation for non-uniform and unequal sized cells.

- Capacity calculation for non-uniform loading of cells.
- Explicit analysis of intra and inter cell interference.
- Shadow and Rayleigh fading analysis.
- Soft handoff analysis.
- Network performance analysis.
- Power control analysis.
- Capacity optimization.

In CCAP the Base Station Database defines the layout of the network. The location of every base station is defined. The number of antennas and the forward power of each antenna are given. Thus omni as well as sectored antennas can be used in the network. The size of the cells can vary depending on the measure of each cell's forward power. The loading of the cells is also defined in the Base Station Database. Thus non-uniform loading is another feature of CCAP.

CCAP calculates the inter cell interference which is the interference that every cell causes on every other cell. It also calculates the intra cell interference which is the interference that users cause on each other within the same cell. Shadow fading and Rayleigh fading as well as power control efficiency are some of the parameters that the user can define to better model the signals and thus get more accurate results.

The soft handoff region is calculated and displayed graphically. The analysis allows every user to be in soft handoff with the two best base stations. It takes into account the probability that a user is in soft handoff and the feasibility of this occurring based on signal level and receiver sensitivity.

CCAP also calculates the network subscriber performance. It uses the Erlang Blocking Probability formula and the user Erlang load to find the number of subscribers that the network can support.

CCAP provides a very cost effective way to optimize capacity. It requires no added hardware, no modification of antenna height, tilt or direction, no added sectors or antennas. Consider a network with a large cell adjacent to a small cell. Users at the boundary of the large cell cause a lot of interference to users at the boundary of the small cell. This is because users transmit power proportional to distance raised to the path loss exponent. Thus a small cell adjacent to a large cell will experience a great deal of interference. Since the capacity of CDMA is interference limited, this phenomenon causes a significant reduction in the capacity of the small cells. In order to alleviate this problem we propose to increase the nominal power of the

users in the small cells by a factor we call the Power Compensation Factor (PCF). CCAP will find the optimal PCF that will maximize the capacity of the network.

2.3 CCAP Development History

The project began in 1995 with the investigation of the capacity that an IS-95 system would have in the Baton Rouge area, Louisiana, USA. We designed a 13-cell configuration for the Baton Rouge city limits. Then we used the data provided by AT&T from their trial in December 1995 to validate the propagation model in the region of interest. By conducting extensive numerical computations we were able to obtain the capacity results for the various cases of fading, imperfections in the power control, different levels of mobile transmitted power and different requirements of signal to noise ratio. The field results verified our theoretical analysis and our algorithms and equations.

The algorithm was further updated in 1996 at Washington University in Saint Louis, Missouri, USA. A graphical user interface was developed and the CCAP tool emerged as a result of a joint effort between Washington University and Teleware, Co. Ltd, Korea. Version 1.0 was completed in the first quarter of 1998.

2.4 Parameters and Functions

2.4.1 Base Station Database

The Base Station Database is where CCAP gets its network information. It is comprised of the following elements:

- Base Station Id: a unique number assigned to each base station
- Easting and Northing: the location of the base station
- Number of antennas or sectors

Then every antenna of every base station has the following elements:

- Direction and beamwidth: of the antenna
- Forward power: given in watts
- Power compensation factor: default value is 1
- Demand Estimator: used to define the loading
- Height and gain

2.4.2 Calculation of Area of Service

The parameters needed for CCAP to calculate the coverage area are the following:

- Base Station Database
- E_{ps} : Receiver sensitivity [-120 dBm]
- F_c : Carrier Frequency [1800 MHz]
- H_{te} : Base Station antenna height [30 m]
- H_{re} : Mobile antenna height [1.5 m]
- dx : Horizontal grid size [150 m]
- dy : Vertical grid size [150 m]

The area is divided into equal sized grids. The default value of the parameters are given in brackets. Please note that all these parameters are user controlled.

2.4.3 Calculation of Inter-Cell Interference

The parameters needed for CCAP to calculate the Inter cell interference are the following:

- m : Path Loss Exponent [4]
- σ_s : Standard deviation for the shadow fading [6 dB]
- Rayleigh: [0] for off [1] for on

- Alpha: Total number of users in a cell divided by the minimum number of users in every cell.

The program will return the value of interference that every cell causes on every other cell.

2.4.4 Calculation of Capacity

The parameters needed for CCAP to calculate the call capacity of every cell are the following:

- W/R : Total bandwidth / User data rate [19.31 dB]
- E_b/I_o : Bit energy / Interference [7 dB]
- ρ : Voice activity factor [3/8]
- σ_c : Standard deviation for the imperfect power control random variable [2.5 dB]
- β : Power compensation factor [1 1 1 ... 1]
- $Target_Pout$: \log_{10} (Blocking Probability) [-2]

The maximum call capacity is calculated for every cell such that the blocking probability is not exceeded. The smallest value defines the capacity of the network.

2.4.5 Calculation of Subscriber Performance

The parameters needed for CCAP to calculate the subscriber performance are:

- erl_user : user load in Erlangs [0.025]
- N is the number of trunks or channels [1]
- B is the blocking probability [0.01]

The maximum sustainable number of subscribers is calculated for every cell and for the entire network using the Erlang Blocking Probability formula.

2.4.6 Calculating the Power Compensation Factor

The Power Compensation Factor is a number for every sector of every cell that is calculated by CCAP to modify the nominal power of every cell in order to increase capacity because of different cell sizes of the network. It has an initial value equal to 1 for every cell. The gradient descent algorithm is used and the values are changed accordingly for some cells as to optimize capacity. The optimal PCF values are returned at the end of the optimization and the new optimal capacity is calculated.

The new PCF is the factor that the nominal power needs to be increased by for every cell. If the value is 1 it means no changes need to be done. If the value is 2, for example, it means double the nominal reverse link power level for the users in that cell. This is achieved by the base station as it instructs the mobiles to increase and decrease their transmitted power during the closed loop power control process.

2.4.7 CCAP Report

CCAP will provide a detailed report providing the following information:

- The value of the inter cell interference of every cell.
- The call capacity of every cell.
- The optimal Power Control Factors (PCF).
- The new optimal capacity.
- The subscriber network performance.

3.0 Algorithms and Equations

3.1 Hata Model

The Hata model is an empirical formulation of the graphical path loss data provided by Okumura, and is valid from 150 MHz to 1500 MHz. Hata presented the urban area propagation loss as a standard formula and supplied correction equations for application to other situations. The standard formula for median path loss in urban areas is given by

$$L_{50}(\text{urban})(\text{dB}) = 69.55 + 26.16 \log f_c - 13.82 \log h_{te} - a(h_{re}) \\ + (44.9 - 6.55 \log h_{te}) \log d$$

where f_c is the frequency (in MHz) from 150 MHz to 1500 MHz, h_{te} is the effective transmitter (base station) antenna height (in meters) ranging from 30 m to 200 m, h_{re} is the effective receiver (mobile) antenna height (in meters) ranging from 1 m to 10 m, d is the T-R separation distance (in km), and $a(h_{re})$ is the correction factor for effective mobile antenna height which is a function of the size of the coverage area. For a small to medium sized city, the mobile antenna correction factor is given by

$$a(h_{re}) = (1.1 \log f_c - 0.7) \cdot h_{re} - (1.56 \log f_c - 0.8) \quad \text{dB}$$

and for a large city, it is given by

$$a(h_{re}) = 8.29(\log 1.54 h_{re})^2 - 1.1 \quad \text{dB} \quad f_c \leq 300 \text{ MHz} \\ a(h_{re}) = 3.2(\log 11.75 h_{re})^2 - 4.97 \quad \text{dB} \quad f_c \geq 300 \text{ MHz}$$

To obtain the path loss in a suburban area the standard Hata formula is modified as

$$L_{50}(\text{dB}) = L_{50}(\text{urban}) - 2[\log(f_c / 28)]^2 - 5.4$$

and for path loss in open rural areas, the formula is modified as

$$L_{50}(\text{dB}) = L_{50}(\text{urban}) - 4.78(\log f_c)^2 + 18.33 \log f_c - 40.98$$

Although Hata's model does not have any of the path-specific corrections which are available in Okumura's model, the above expressions have significant practical value. The

predictions of the Hata model compare very closely with the original Okumura model, as long as d exceeds 1 km. This model is well suited for large cell mobile systems, but not

personal communications systems (PCS) which have cells on the order of 1 km radius.

3.2 PCS Extension to Hata Model

The European Co-operative for Scientific and Technical research (EURO-COST) formed the COST-231 working committee to develop an extended version of the Hata model. COST-231 proposed the following formula to extend Hata's model to 2 GHz. The proposed model for path loss is

$$L_{50}(\text{urban}) = 46.3 + 33.9 \log f_c - 13.82 \log h_{te} - a(h_{re}) \\ + (44.9 - 6.55 \log h_{te}) \log_{10} d + C_M$$

where $a(h_{re})$ is defined above.

$C_M = 0$ dB for medium sized city and suburban area

$C_M = 3$ dB for metropolitan centers

The COST-231 extension of the Hata model is restricted to the following range of parameters:

f_c : 1500 MHz to 2000 MHz

h_t : 30 m to 200 m

h_r : 1 m to 10 m

d : 1 km to 20 km

3.3 Single Cell Reception – Hard Handoff

Suppose first that only a single cell's pilot is being tracked at any one time, and that handoff between cells is performed at the cell boundary. This is idealized because such a process would lead to multiple rapid handoffs for users at or near the boundary. This condition may be alleviated by requiring handoffs to occur only when the second cell's pilot strength is sufficiently above that of the first. Nevertheless, we shall use this idealized hard-handoff model first and then later generalize to include soft handoff.

Assume we have two cells i and j . A user a located at coordinates (x, y) and served by the base station of cell i , is at a distance $r_i(x, y)$ from its own base station. Let $r_j(x, y)$ be the distance from the same user a to base station j as shown in Figure 2.

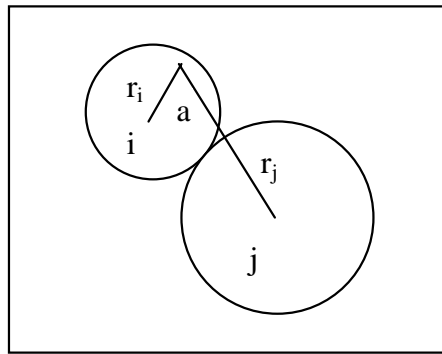


Figure 2

Let Ku_i be the average number of users in cell i . We define the density K as:

$$K = \frac{Ku_i}{Area_i} = \frac{Ku \min \cdot \alpha_i}{Area_i}$$

Since the user at (x, y) is communicating through the nearest base station, it will also be power controlled by that base station. The user's transmitter power gain thus equals the propagation loss for that cell. This propagation loss is generally modeled as the product of the m th power of distance and a log-normal component representing shadowing losses. This model represents slowly varying losses, even for users in motion, and applies to both

the reverse and forward links. The more rapidly varying Rayleigh fading losses are not included here but will be included later. Consequently, the relative average interference at cell j 's base station caused by *all* users in cell i is given by

$$I_{ij} = E \iint_{cell_i} \left[\frac{r_i^m}{r_j^m} \cdot \frac{10^{\zeta_i/10}}{10^{\zeta_j/10}} \right] K dA = E \iint_{cell_i} \frac{r_i^m}{r_j^m} \cdot \frac{10^{\zeta_i/10}}{10^{\zeta_j/10}} \cdot \frac{Ku \min \cdot \alpha_i}{Area_i} dA$$

ζ is the decibel attenuation due to shadowing, with zero mean and standard deviation σ_s . m is the path loss exponent. Thus, the denominator of the bracketed term is the propagation loss to the given base station, while the numerator is the gain adjustment through power control by the nearest base station. Note finally that all parameters are position dependent and deterministic except for ζ_i and ζ_j , which are random but do not depend on position.

Define f_{ij} as the mean inter-cell interference normalized by the minimum number of users per cell, i.e.

$$f_{ij} = \frac{I_{ij}}{Ku \min}$$

After taking the expectation and changing integration over to summation by dividing the area into small equal sized grids, f_{ij} becomes

$$f_{ij} = e^{b^2(\beta \cdot \sigma_s)^2} \left[\frac{\alpha_i}{(\# \text{ grids for } cell_i)} \sum_{cell_i} \left(\frac{r_i}{r_j} \right)^m \right]$$

where $b = \frac{1}{\sqrt{2}}$ and $\beta = \frac{\text{Ln}(10)}{10}$

3.4 Access Outage – Single Cell and Perfect Power Control

The capacity of a multiple access network is measured by the average number of users receiving service at a given time with a given level of quality, which includes requirements for both accuracy and service availability. Availability is defined as the complement of the probability that a user does not receive service at any given time because all slots are

currently assigned to calls – a situation that evokes a busy signal. In a wireless system, the total number of available slots depends on total bandwidth, data rate per user, and frequency reuse factor, all of which determine the quality of the call in terms of availability or accuracy or both.

In spread spectrum systems, since all users occupy the same frequency spectrum and time allocation, there are no slots. The system is strictly interference limited. We assume initially a single cell occupied by K_u perfectly power controlled users, so that each is received by the base station at the same power level. However, each user's digital input may be intermittent: a voice call with variable rate based on voice activity detection, or an interactive message that requires a response before sending new data. During inactive periods, the user's signal power is suppressed. Then for a total bandwidth occupancy W Hz for all users with equal rates R bits/s, background noise N_o watts/Hz and equal, perfectly controlled bit energies E_b , the total average power received by the cell, assuming stationary arrivals and user activity, is

$$\text{Total Power} = \sum_{i=1}^{K_u} v_i E_b R + N_o W$$

Where v_i is a binary random variable indicating whether or not the i th user is active at any instant. Thus $\Pr(v_i = 1) = \rho$, the voice activity factor or fraction of the time during which the user's signal is present. Since the total received power is the sum of noise, interference power, and the desired user power, the average noise-plus-interference power, denoted by $I_o W$ is

$$I_o W = \sum_{i=1}^{K_u} v_i E_b R + N_o W$$

For dynamic range limitations on the multiple access receiver of bandwidth W (as well as to guarantee system stability), it is desirable to limit the total received noise-plus-interference power-to-background noise. Thus we require

$$\frac{I_o}{N_o} < \frac{1}{\eta} \text{ where } \eta < 1 \text{ and typically } \eta = 0.25 \text{ to } 0.1$$

Combining the previous equations yields

$$\sum_{i=1}^{K_u} v_i < \frac{(W/R)(1-\eta)}{E_b/I_o} \cong K_o(1-\eta) \cong K'_o$$

where both the v_i and K_u are independent random variables. When this condition is not met, the system will be deemed to be in the outage condition. This condition is only temporary, remedied without intervention by the random variation of the variables. The power control mechanism can accelerate the process and guarantee stability by reducing the E_b/I_o requirement for all users. In either case, the probability of outage, P_{out} is upper bounded slightly by including the desired signal variable, v_i in the summation. Therefore,

$$P_{out} = \Pr \left[Z = \sum_{i=2}^{K_u} v_i > K'_o \right] < \Pr \left[Z = \sum_{i=1}^{K_u} v_i > K'_o \right]$$

P_{out} is obtained through approximating the Poisson by a Gaussian variable with the same mean and variance. Thus:

$$P_{out} \approx Q \left[\frac{K'_o - E(Z)}{\sqrt{Var(Z)}} \right] \text{ where } Q \text{ is the complementary error function.}$$

3.5 Access Outage – Multiple Cell and Imperfect Power Control

First taking into account multiple cells, users controlled by other cell base stations introduce interference power into a given base station whose average is fK_u , where K_u is the average number of active users per cell. Continuing with the perfect power control assumption, which we shall abandon shortly, this means that all other cell users can be accounted for in the outage probability expression by additional terms having $v_i \leq 1$, when active. Thus, the probability of outage becomes

$$P_{out} = \Pr \left[Z = \sum_{i=1}^{K_u(1+f)} v_i > K'_o \right]$$

We come finally to the most important issue of all, the effect of imperfect power control on capacity. A user that is controlled to a desired E_b/I_o level will exhibit a received E_b/I_o level at the desired cell base station that varies according to a log-normal distribution with a standard deviation on the order of 1.5 to 2.5 dB. With this condition, the outage probability derivation needs to be modified so that the constant value of E_b for all users is replaced by a variable $E_{b_i} \cong \varepsilon_i E_{b_o}$, which is log-normally distributed. By so doing, and accounting also for inter-cell interference, we obtain

$$P_{out} = \Pr \left[Z' = \sum_{i=1}^{K_u(1+f)} \varepsilon_i \cdot v_i > K_o' \right]$$

As we did for perfect power control, we can also obtain the Gaussian approximation. Thus approximating the distribution of Z' , we obtain

$$P_{out} \approx Q \left[\frac{K_o' - E(Z')}{\sqrt{\text{Var}(Z')}} \right]$$

After taking the expectation and the variance, P_{out} becomes

$$P_{out} = Q \left[\frac{\beta_j \cdot K_o' - (\beta_j \alpha_j + \sum_{\forall i, i \neq j} \beta_i \cdot f_{ij}) \cdot K_{umin} \cdot \rho \cdot e^{(b \cdot \sigma_c^2)/2}}{\sqrt{(\beta_j^2 \alpha_j + \sum_{\forall i, i \neq j} \beta_i^2 \cdot f_{ij}) \cdot K_{umin} \cdot \rho \cdot e^{(b \cdot \sigma_c^2)}}} \right]$$

Where σ_c is the standard deviation of the Gaussian random variable with zero mean that models the imperfect power control.

3.6 Soft Handoff Reception

To approach the performance of a soft handoff system, we next consider other cell interference when the user is permitted to be in soft handoff to only its two nearest cells. In soft handoff, the user is connected to two or more cell base stations, and instantaneously, on a frame-to-frame basis, the better frame received by either base station is accepted by the network.

Again, we consider the zeroth cell. The region for which this cell's base station can be in soft handoff with the user, which we denote by S_o , is the six pointed star that contains the cell as shown in Figure 3.

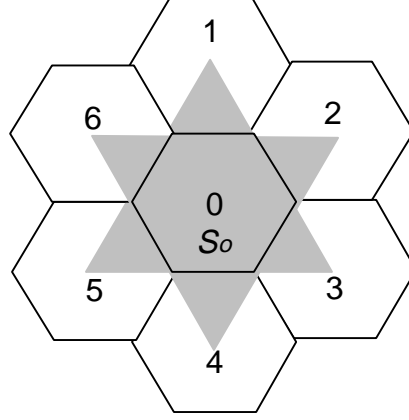


Figure 3

Within S_o , any user that is communicating with one of the six nearest neighbors will introduce interference into the zeroth base station. But this happens only if the propagation loss to that neighbor is less than to the zeroth base station, in which case it is power controlled by the former. Thus, the mean total interference to the zeroth base station from within the S_o region is

$$I_{S_o} = \iint_{S_o} \frac{r_1^m}{r_o^m} E \left[10^{(s_1 - s_o)/10}; r_1^m \cdot 10^{s_1/10} < r_o^m \cdot 10^{s_o/10} \right] K dA$$

where the expectation is over the sample space for which the inequality is satisfied.

Define

$$M_i(x, y) = 10 m \log_{10} r_i(x, y)$$

Substituting and taking the expectation

$$I_{S_o} = e^{b^2(\beta\sigma_s)^2} \iint_{S_o} \frac{r_1^m}{r_o^m} Q \left[\sqrt{2b\beta\sigma_s} + \frac{M_1 - M_o}{\sqrt{2b\sigma_s}} \right] K dA$$

Now for the complementary region $\overline{S_o}$ (outside the six-pointed star), the two nearest base stations involved in a potential soft handoff do not include the zeroth. We let the subscripts 1 and 2 denote the two nearest base stations, which include all contiguous pairs of cells over the entire plane. Then the total mean interference to the zeroth base station from the $\overline{S_o}$ region is

$$\begin{aligned}
I_{S_o} &= \iint_{\overline{S_o}} \frac{r_1^m}{r_o^m} E \left[10^{(s_1-s_o)/10}; r_1^m \cdot 10^{s_1/10} < r_2^m \cdot 10^{s_2/10} \right] K dA \\
&\quad + \iint_{\overline{S_o}} \frac{r_2^m}{r_o^m} E \left[10^{(s_2-s_o)/10}; r_2^m \cdot 10^{s_2/10} < r_1^m \cdot 10^{s_1/10} \right] K dA \\
&\equiv I_1 + I_2
\end{aligned}$$

Evaluating the first integral

$$I_1 = e^{b^2(\beta\sigma_s)^2} \iint_{\overline{S_o}} \frac{r_1^m}{r_o^m} Q \left[\frac{b\beta\sigma_s}{\sqrt{2}} + \frac{M_1 - M_2}{\sqrt{2}b\sigma_s} \right] K dA$$

Now the second integral I_2 is the same as I_1 , with M_1 and M_2 interchanged. But since subscripts 1 and 2 represent the two nearest cells, they are interchangeable and hence $I_1 = I_2$.

Thus combining the previous equations and using $b = 1/\sqrt{2}$, we obtain the relative interference at the zeroth cell base station from all users not controlled by its base station.

Note finally that although we have implicitly assumed an omnidirectional base station antenna, because of the uniform user loading assumption that implies circular symmetry, all results apply also to a single sector of a multi-sectored cell antenna.

3.7 Rayleigh Fading

In this section we derive the reverse link capacity of multiple-cell CDMA system for the case of shadow fading as well as Rayleigh fading. It is assumed that the power control mechanism overcomes both large scale path loss and shadow fading. It does not, however, overcome the fast fluctuations of the signal power associated with Rayleigh fading.

Consider an inter sector user at a distance r_l from the cell site with which it is associated. Let r_o denote the distance of this user from the zeroth base station. Let X_o denote the Rayleigh random variable that represents the fading on the path from this user to the zeroth base station. The average of X_o^2 is the log-normal fading on that path. In other words, $E[X_o^2 | \zeta_0] = 10^{-\zeta_0/10}$. The interference from user a at the zeroth base station is given by

$$I(r_0, r_1) = r_1^m \cdot 10^{\zeta_1/10} \cdot r_0^{-m} \cdot X_o^2$$

Therefore, the total inter sector interference is given by

$$I = E \iint \left[\frac{r_1^m}{r_0^m} \cdot 10^{\zeta_1/10} \cdot X_o^2 \right] \cdot K dA$$

Taking the expectation

$$\begin{aligned} E\left(10^{\zeta_1/10} \cdot X_o^2\right) &= E\left(E\left(10^{\zeta_1/10} \cdot X_o^2 \mid \zeta_0, \zeta_1\right)\right) \\ &= E\left(10^{\zeta_1/10} E\left(X_o^2 \mid \zeta_0, \zeta_1\right)\right) \\ &= E\left(10^{\zeta_1/10} \cdot 10^{-\zeta_0/10}\right) \end{aligned}$$

Then defining

$$\beta = \frac{\ln(10)}{10} \text{ and } x = \zeta_1 - \zeta_0$$

Where x is a Gaussian random variable with zero mean, and since ζ_1 and ζ_0 are independent, $\text{var}(\zeta_1 - \zeta_0) = 2\sigma_s^2$.

Substituting, the total inter sector interference becomes

$$\begin{aligned} I &= E\left(e^{\beta x}\right) \iint \frac{r_1^m}{r_0^m} K dA \\ &= e^{(\beta\sigma_s)^2} \iint \frac{r_1^m}{r_0^m} K dA \end{aligned}$$

Recall that the density K is

$$K = \frac{Ku_i}{Area_i} = \frac{Ku \min \cdot \alpha_i}{Area_i}$$

where Ku_i be the average number of users in cell i and f_{ij} as the mean inter-cell interference normalized by the minimum number of users per cell, i.e.

$$f_{ij} = \frac{I_{ij}}{Ku \min}$$

After changing integration over to summation by dividing the area into small equal sized grids, f_{ij} becomes

$$f_{ij} = e^{(\beta \cdot \sigma_s)^2} \left[\frac{\alpha_i}{(\# \text{ grids for cell}_i)} \sum_{cell_i} \left(\frac{r_i}{r_j} \right)^m \right]$$

3.8 Optimization of Power Compensation Factor

In order to optimize the capacity by optimizing the Power Compensation Factor which we also call Beta the gradient descent method is used. Beta is an m dimensional vector where m is the total number of sectors in the network. A value of Beta for a sector equal to one means the mobiles in that sector are operating at a nominal power level. The final values of Beta are the factor that the required nominal power for each sector must be multiplied by. This new power level will optimize the network and increase capacity.

3.9 Subscriber Capacity

All the capacity results that have been calculated have been in terms of the number of simultaneous users per channel per sector. Next, we convert these capacities to units of subscribers per sector, per cell and for the network that the system can support. For these calculations, we use a blocking probability of 1%. We assume 1 channel allocation per base station and a load of 25 mErlangs per subscriber. The Erlang-B formula is given by

$$E(v, N) = \frac{v^N}{N!} \left(\sum_{n=0}^N \frac{v^n}{n!} \right)^{-1}$$

where $E(v,N)$ is the loss probability, v is the flow of traffic offered expressed in Erlang, and N is the total number of trunks.

So given the number of trunks or channels, N , and the blocking probability, B , we wish to find the offered load in Erlangs. The following formulas are used to approximate the offered load

$$Erlangs(N, B) = \frac{2}{((2 - B) / B)^{1/N} - 1} \quad \text{if } N \leq 3$$

$$Erlangs(N, B) = \frac{1}{4} \left(2\sqrt{N} - \left(2 \log \left(\frac{4}{B\sqrt{2\pi N} (4 - B\sqrt{2\pi N})} \right) \right)^{1/2} \right)^2 + \frac{1}{4} \quad \text{if } N > 3$$

As an example, for a capacity of 22 users per sector and 1% blocking probability, this allows for 13.6 Erlangs of traffic. With 25 mErlangs of traffic per subscriber, this translates to 544 subscribers per channel per sector. Calculating the number of subscribers for every sector and adding the results gives the total number of subscribers for the network.

3.10 Software Flow Chart

Figure 4 presents an overview of the program. Using the Base Station database, and the values of receiver sensitivity, E_{ps} , the frequency carrier, F_c , the horizontal and vertical grid size, dx and dy , the transmitter antenna height, H_{te} , and the mobile antenna height, H_{re} , the total area of coverage is first calculated.

Then for every grid point the serving Base Station and the sector number is found. This information is stored in two matrices, map_BS and map_SEC . Also the second strongest serving Base Station and sector number is found. This information is stored in two matrices, map_BSSOFT and $map_SECSoft$.

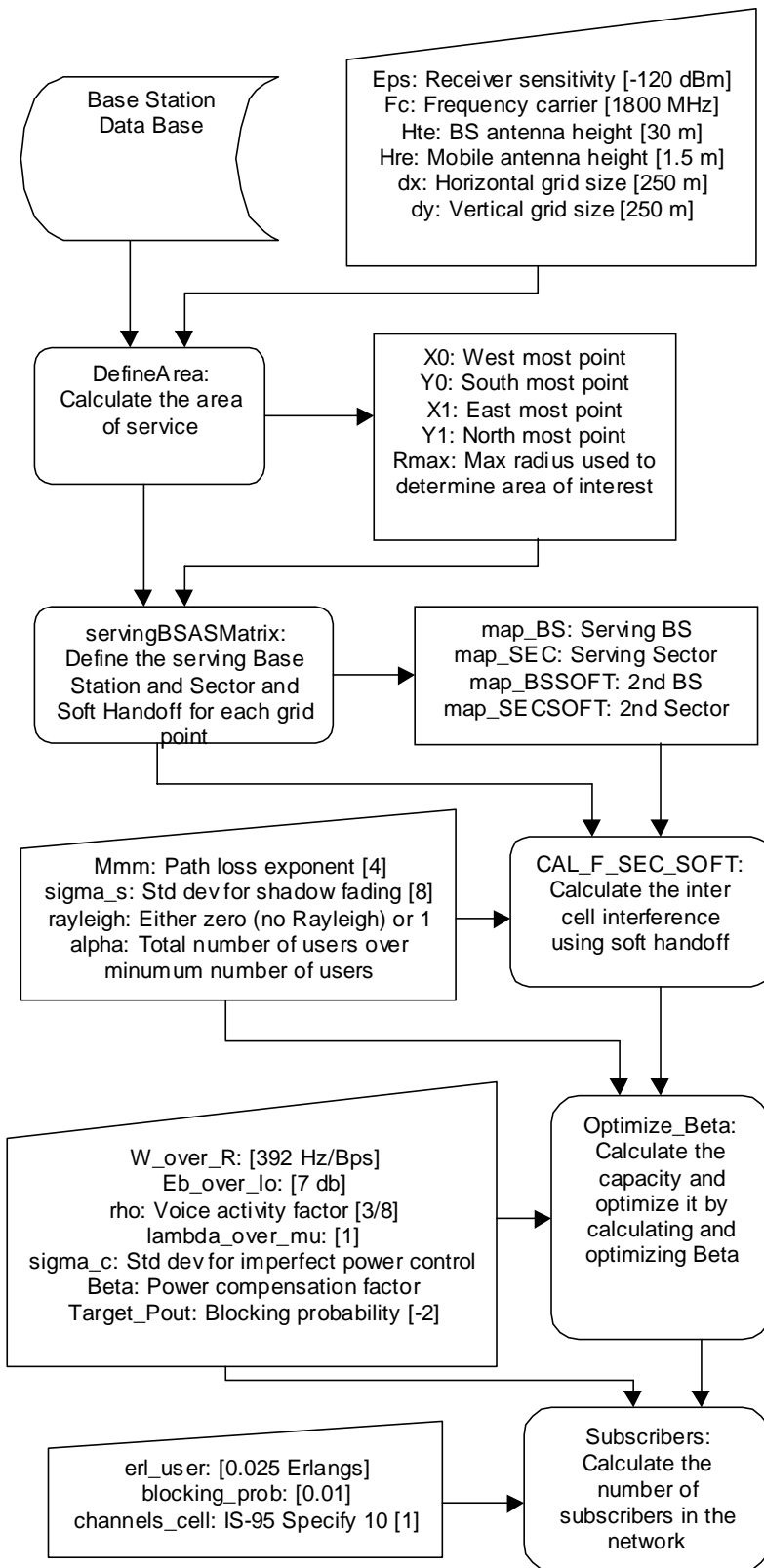


Figure 4

Then using the path loss exponent, M_{mm} , the standard deviation for the shadow fading random variable, σ_s , the number of users in every sector, $(\alpha * K_{u_{min}})$, and the value of the variable *rayleigh* (which is either 0 for no Rayleigh or 1 for use Rayleigh analysis), the inter cell or inter sector interference is calculated.

Next capacity is calculated and the values of Beta are optimized to optimize capacity. The inputs needed are W_{over_R} , $E_b_{over_{No}}$, ρ (the voice activity factor), $\lambda_{over_{\mu}}$, σ_c , and *Target_Pout*.

Once the network is optimized the total number of subscribers that can be serviced is obtained. The number of users in every sector is also adjusted for using soft handoff.

4.0 Test Results and Demos

In order to demonstrate how the Power Compensation Factor will increase capacity, consider the network shown in Figure 5. The network is made up of three large cells and four small cells. Each cells uses three sectored antennas.

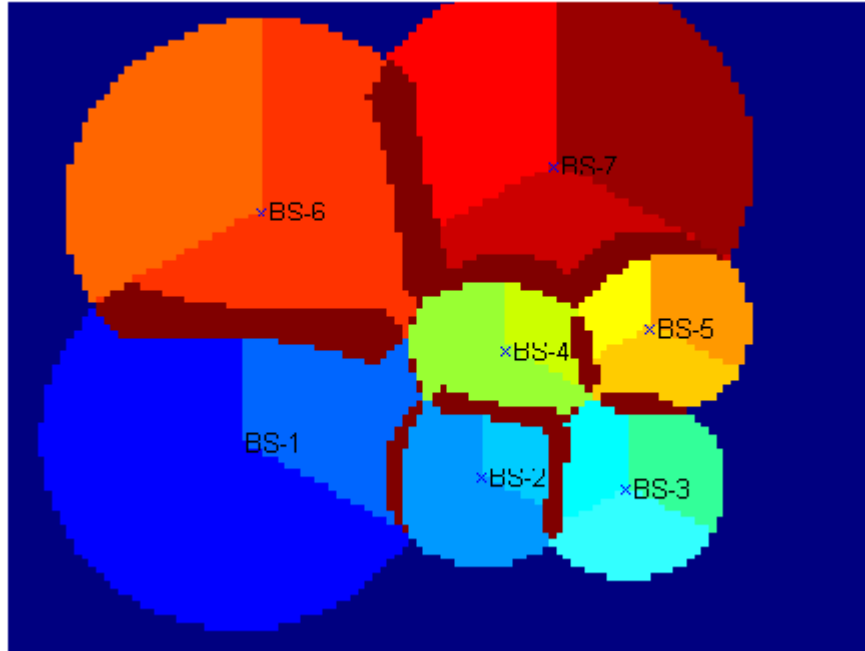


Figure 5

Four different scenarios were run. The capacity before (x) and after optimization (*) was found for each sector in each of the four scenarios as shown in Figure 6. In the first scenario the default parameters of the CCAP program which were presented earlier were used. In the second scenario, perfect power control is assumed. In the third scenario, Rayleigh interference is ignored. In the fourth scenario, the processing gain was increased from 19.31 dB to 21.1 dB.

The choice of these four scenarios is to try to capture the different aspects of the network: changing the power control efficiency which affects intra cell interference, considering or ignoring Rayleigh fading which affects inter cell interference, and modifying a system parameter which affects the capacity in general.

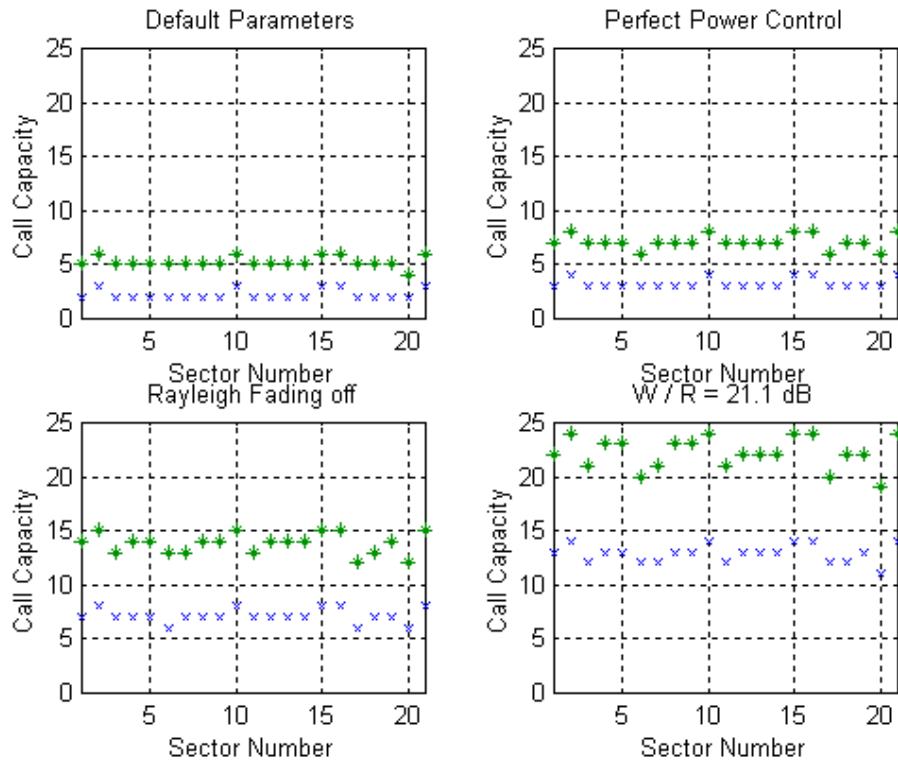


Figure 6

In each scenario the current capacity (x) and the optimized capacity (*) were plotted for each sector. The values of the Power Compensation Factor that gave us this increase in capacity are shown in Figure 7. The PCF's for sector 4 and sector 10 need to be increased by a factor of 1.5 and 2.2 respectively. Note that the sectors are numbered counter clockwise for each base station so sectors 4 and 10 are the upper left sectors of base stations 2 and 4. Our numerical results match our theoretical results in terms of increasing the PCF of small sectors that are adjacent to large ones.

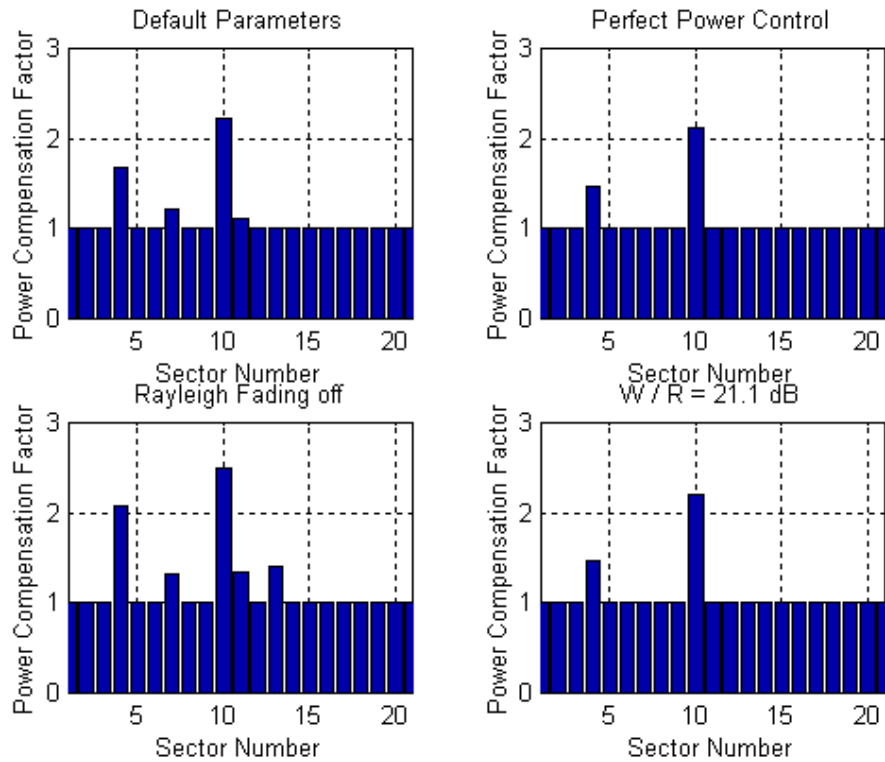


Figure 7

What is very important to note that the pattern of the Optimized Power Compensation Factors is very similar for each scenario even though the scenarios themselves are very different in terms of the parameters that have changed. It is fact that allows us to promise the capacity increase if the new PCF's were implemented.

CCAP will also calculate the network subscriber performance. The number of subscribers for every cell for each scenario are shown in Figure 8.

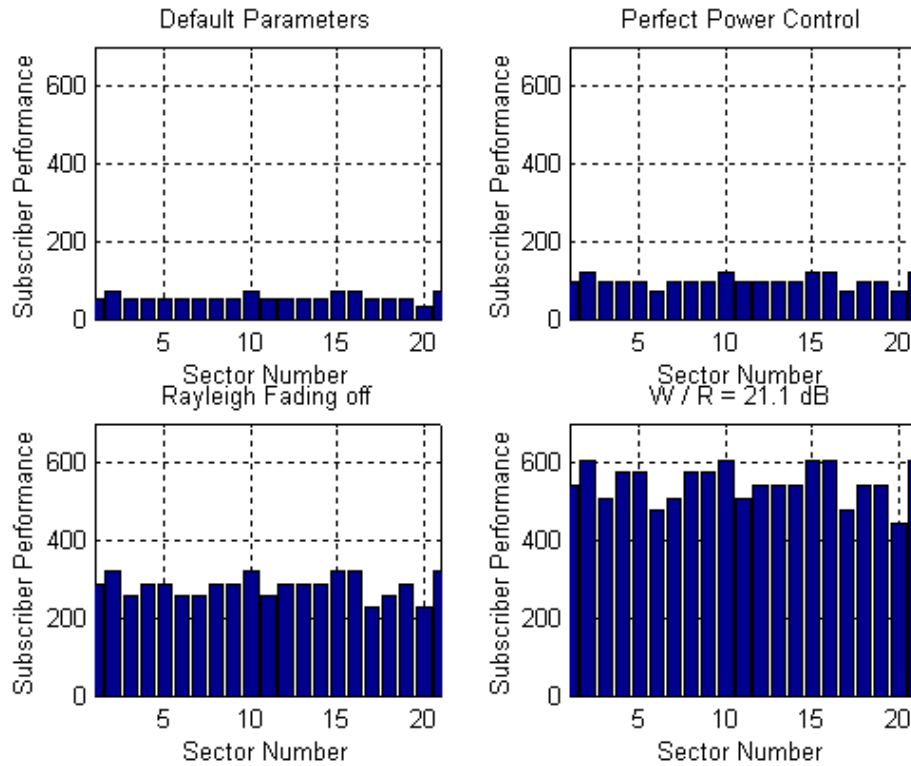


Figure 8

CCAP is a very versatile tool. It provides the user with an accurate calculation of the current network capacity. It provides a very cost effective way then to increase that capacity. It calculates the optimal Power Compensation Factors and the new optimized capacity. Finally it finds the network subscriber performance.