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**CDMA capacity analysis**

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# Contents

<b>1. INTRODUCTION .....</b>	<b>3</b>
<b>2. BASIC CDMA UPLINK CAPACITY FORMULA .....</b>	<b>3</b>
<b>3. VOICE ACTIVITY .....</b>	<b>4</b>
<b>4. INTERFERENCE FROM OTHER CELLS (INTERCELL INTERFERENCE) .....</b>	<b>4</b>
4.1 PROPAGATION MODEL AND CELL LAYOUT.....	4
4.2 DISTRIBUTION OF USERS .....	6
4.3 INTERCELL INTERFERENCE RATIO IN CASE OF HARD HAND OVER.....	6
4.4 INTERCELL INTERFERENCE RATIO IN CASE OF SOFT HAND OVER .....	7
<b>5. SECTORED CELLS .....</b>	<b>9</b>
<b>6. ERLANG CAPACITY .....</b>	<b>9</b>
<b>7. ERLANG CAPACITY WITH IMPERFECT POWER CONTROL .....</b>	<b>11</b>
<b>8. ERLANG CAPACITY OF DOWNLINK (FORWARD LINK).....</b>	<b>12</b>
<b>9. SIMULATIONS.....</b>	<b>14</b>
9.1 ENVIRONMENTS .....	14
9.2 SERVICES .....	15
9.3 STATIC SIMULATIONS .....	16
9.4 DYNAMIC SIMULATIONS.....	17
<b>10. CONCLUSION .....</b>	<b>17</b>
<b>11. REFERENCES .....</b>	<b>18</b>

## ABSTRACT

In this document both analytical and simulation methods for CDMA network capacity are introduced. The effects of various CDMA network structures and radio management algorithms are presented separately from the analytical perspective. In the simulation section the structure of static CDMA simulator is presented. The gains and drawbacks of using dynamic simulator instead of static simulator is discussed. In addition analytical and simulated capacity figures are compared.

## 1. INTRODUCTION

In this presentation and document an introduction of CDMA capacity analysis is given for speech service in hexagonal network environment, see Figure 1. First the basic principles and characteristic features effecting on the CDMA uplink capacity are introduced one by one and spectrum efficiencies of IS-95 [2] and WCDMA [6] are presented. Next the key differences for CDMA downlink capacity are analysed. In the last section of the document different environment and services are introduced and basic techniques for both static and dynamic CDMA capacity simulations are given. The analysis part of the document and the presentation follows closely ideas presented in [1].

## 2. BASIC CDMA UPLINK CAPACITY FORMULA

A good starting point for CDMA system capacity analysis is to derive the relation between required  $E_b/N_0$  and the amount of simultaneously transmitting users in a cell, [7]. Consider a case of  $N$  users simultaneously transmitting, in the receiver demodulation processes a composite signal containing the desired signal having power  $S$  and  $(N-1)$  interfering signals each also having power  $S$ . Thus we assume ideal power control. At each receiver input the signal-to-noise power ratio can be expressed as

$$\text{SNR} = \frac{S}{(N-1)S} = \frac{1}{(N-1)} \quad (1)$$

After despreading process (processing gain  $G$ ) signal-to-noise ratio becomes:

$$\frac{E_b}{N_0} = \frac{G}{(N-1)} \quad (2)$$

where  $G=W/R$  is the processing gain,  $W$  is the total bandwidth of the CDMA signal and  $R$  is information bit rate. After including Gaussian noise to 1, Equation 2 changes slightly:

$$\frac{E_b}{N_0} = \frac{G}{(N-1) + \frac{\alpha}{S}} \quad (3)$$

Solving Equation 3 for  $N$  we get:

$$N = 1 + \frac{W/R}{E_b/N_0} - \frac{\alpha}{S} \quad (4)$$

Equation 4 gives CDMA capacity as [users/carrier], where each user has information bit rate R [b/s]. Carrier bandwidth W is given in hertz [Hz], required  $E_b/N_0$  is in linear scale and  $\alpha$  and S are given in watts [W]. It is straightforward calculation to give the capacity in [users/MHz] or [kbits/MHz]. It is important to note that several key assumptions are made while Equation 4 is derived.

1. Isolated cell, no inter cell interference
2. Perfect power control, variation of channel fading are erased by power control
3. No maximum power limit
4. No code limit

Thus Equation 4 is the upper bound for uplink system capacity.

### 3. VOICE ACTIVITY

Normally during a telephone conversation while one is speaking the other is listening. This phenomenon can be monitored by the cellular system and the power can be reduced during the silent periods. Here CDMA, e.g. IS-95 has a clear advantage over GSM, because in GSM even if transmitting power is turned off connection occupies same amount of radio resources. This is not the case in CDMA, because there are more codes per carrier than a carrier can use simultaneously. According to measurement active speech ratio of each party is roughly 3/8, thus 25% of time both parties are silent simultaneously. Theoretically, voice activity factor  $\varpi=3/8$  can be easily added to Equation 3.

$$\frac{E_b}{N_0} = \frac{G}{(N-1)\varpi + \frac{\alpha}{S}} \quad (5)$$

This would increase the capacity increases up to 8/3, if system is interference limited,  $\alpha \ll S$ . This analysis however requires that N is large, in order to have the ratio of simultaneously active users around 3/8.

### 4. INTERFERENCE FROM OTHER CELLS (INTERCELL INTERFERENCE)

In order to study the other cell interference, we must first make assumptions of the propagation conditions, cell layout and the distribution of the users and derive mathematical notation for these assumptions.

#### 4.1 Propagation model and cell layout

In order to study intercell interference of any multiple access scheme one must define a propagation model L.

$$L = \frac{\text{transmitted signal [W]}}{\text{received signal [W]}} \quad (6)$$

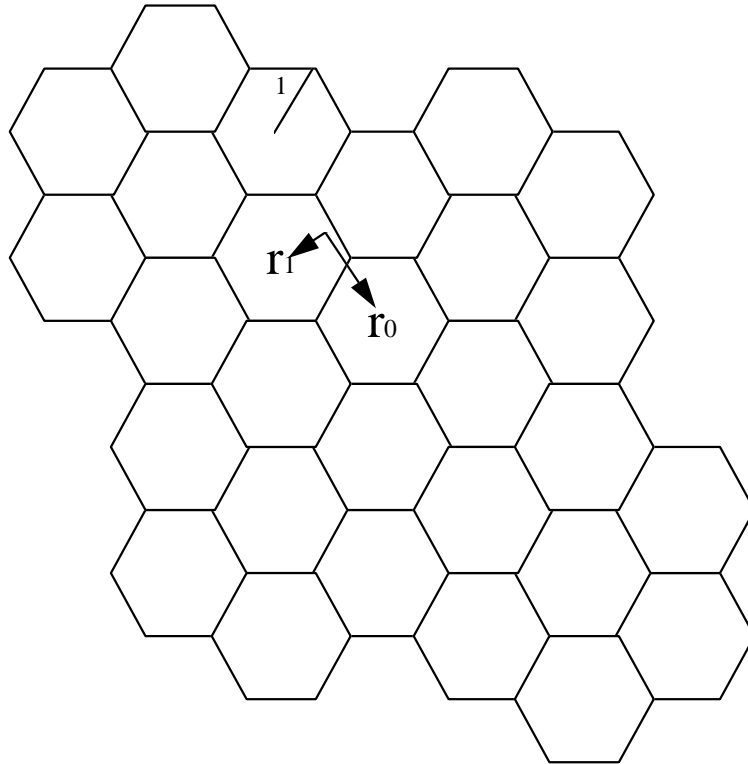
For network capacity analysis point of view it is enough to model  $L$  as function of distance between the transmitter and receiver,  $r$ , and a log-normal distributed random variable  $\varepsilon$  representing shadowing losses. With  $\varepsilon$  we model slowly varying losses, not channel fading [2]. Let's define  $L$  according to [2] and [3]:

$$L(r, \varepsilon) = r^m 10^{\varepsilon/10} \quad (7)$$

where  $m$  is distance attenuation exponent. In dB scale Equation 7 becomes:

$$L(r, \varepsilon) = 10 \cdot m \cdot r + \varepsilon \quad (8)$$

where  $e$  is now normally distributed random variable. Measurements reported [2] and [3] suggest that  $e \sim N(0, \sigma)$ , where  $\sigma$  is around 8 dB. The propagation exponent  $m$  takes value from 2 to 6 depending on environment. Also the measurement of distance  $r$  will depend on environment, if traditional hexagonal macro cell layout is applied, Figure 1,  $r$  is norm of  $l_2$  space  $r^2 = x^2 + y^2$ . If Manhattan type layout is applied, Figure 4,  $r$  is norm of  $l_1$  space,  $r = x + y$ . In the analysis part of this paper we restrict ourselves to the **hexagonal environment**.



*Figure 1. Example layout for hexagonal (macro) layout. Cell radius is normalized to unity.*

Further let's define correlation between slow fading components of any two transmitters  $\varepsilon_i$  and  $\varepsilon_j$  to a single receiver according to Equation 6:

$$\begin{aligned}\varepsilon_i &= 0.5\xi + 0.5\xi_i \\ \varepsilon_j &= 0.5\xi + 0.5\xi_j\end{aligned}\quad (6)$$

$$\begin{aligned}\text{where } E(\varepsilon_i) &= E(\varepsilon_j) = E(\zeta_i) = E(\zeta) = 0, \\ \text{var}(\varepsilon_i) &= \text{var}(\varepsilon_j) = \text{var}(\zeta_i) = \text{var}(\zeta) = \sigma^2, \\ E(\zeta_i \zeta_j) &= 0 \text{ for all } i \\ E(\zeta_i \zeta_j) &= 0 \text{ for all } i \neq j\end{aligned}$$

Justification for this correlation is (in addition of better performance) that the slow fading is sum of two components, near the receiver, which is common to all transmitter receiver pairs and one near the transmitter which is independent for all transmitters. Note that the same correlation applies also for downlink case of one transmitter and several receivers.

## 4.2 Distribution of users

We assume uniform distribution of users throughout the cellular network. Let  $k_u$  be the average number of users per cell, then the amount of users per unit area is:

$$\kappa = \frac{2k_u}{3\sqrt{3}} \quad (9)$$

In equation 9, hexagonal cell shape is assumed and hexagon size is normalised to unity, see Figure 1.

## 4.3 Intercell interference ratio in case of hard hand over

Let the distance from a mobile to its serving base station, BTS1 be  $r_1(x,y)$  and the distance from the same mobile to an interfering base station, BTS0 be  $r_0(x,y)$ . Since the mobile is served by BTS 1 it is also power controlled by BTS1. Thus the average *relative* interference at the BTS 0 due to the all other BTSs in the area denoted by  $S_0$ , is

$$I_{S_0} = E \iint_{S_0} \left[ \frac{r_1^m(x,y) 10^{\varepsilon_i/10}}{r_0^m(x,y) 10^{\varepsilon_0/10}} \right] \kappa dA(x,y) \quad (10)$$

defining  $R_1(x,y) = r_1(x,y)/r_0(x,y)$  and  $\beta = \ln(10)/10$  and using relations 6 and 7 we can rewrite 10 as:

$$I_{S_0} = e^{(\beta\sigma)^2/2} \left[ \frac{2k_u}{3\sqrt{3}} \iint_{S_0} R_1^m(x,y) dA(x,y) \right] \quad (11)$$

Normalising other cell interference by the number of users per each BTS we get:

$$f = \frac{I_{S_0}}{k_u} = e^{(\beta\sigma)^2/2} \left[ \frac{2}{3\sqrt{3}} \iint_{S_0} R_1^m(x,y) dA(x,y) \right] \quad (12)$$

where  $f$  is relative other cell interference factor. In Table 1 we have solved  $f$  by means of numerical integration with several attenuation exponents,  $m$ , and standard deviations of the slow fading component,  $\sigma$ .

$\sigma$ dB	$m=3$	$m=4$	$m=5$
0	0.77	0.44	0.30
4	1.18	0.67	0.46
8	4.21	2.38	1.64
12	35.1	19.8	13.7

Table 1. Inter cell interference ratio in case of hard hand over. Table is obtained from [1].

The derived  $f$  can be incorporated into 3 to achieve **uplink network capacity of a CDMA system presented in Equation 13.**

$$N = 1 + \frac{1}{(1+f)\varpi} \left( \frac{W/R}{E_b/N_0} - \frac{\alpha}{S} \right) \quad (13)$$

which is valid iff  $N > 1$ , see Equation 1.

#### 4.4 Intercell interference ratio in case of soft hand over

As seen from Table 1, the interference from the other cells a major problem. A CDMA specific solution for inter cell interference is **soft handover**. When a mobile is in a soft handover, it communicates simultaneously with several base stations. In the analysis part of this document we restrict ourselves to the case where a mobile can be in soft handover only with 2 base stations. The idea can easily be extended to cover cases where mobile is in soft handover with more than 2 base stations, but mathematical notation becomes quite complicated. Let's consider the center cell, BTS 0, in Figure 2.

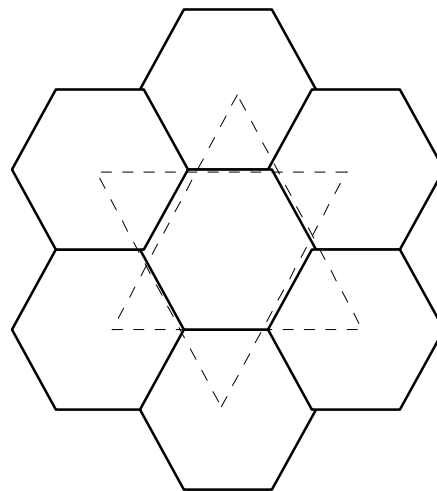


Figure 2. Soft handover region.

In addition to the hexagonal area BTS0 covers also the mobiles outside the hexagon but inside the six-pointed star can be in soft handover with BTS 0. Let's name the area covered by the six-pointed star as  $S_0$ . Now any mobile inside  $S_0$  that communicates with base station other than BTS 0 causes inter cell interference to BTS 0. But this is case only if the propagation loss is to the neighboring base station is less than to BTS 0. Otherwise it is power controlled by BTS 0 and included into own cell interference. Thus the mean inter cell interference caused by mobiles inside  $S_0$  is:

$$I_{S_0} = \iint_{S_0} \kappa \left[ R_1^m(x, y) E \left[ 10^{(\epsilon_1 - \epsilon_0)/10}; r_1^m(x, y) 10^{\epsilon_1/10} < r_0^m(x, y) 10^{\epsilon_0/10} \right] dA(x, y) \right] \quad (14)$$

$$I_{S_0} = \iint_{S_0} \left[ R_1^m(x, y) E \left[ 10^{(\epsilon_1 - \epsilon_0)/10}; r_1^m(x, y) 10^{\epsilon_1/10} < r_0^m(x, y) 10^{\epsilon_0/10} \right] \frac{2k_u}{3\sqrt{3}} dA(x, y) \right]$$

Defining  $M_i(x, y) = 10 \log_{10} r_i(x, y)$  and applying slow fading correlation equation (6) we can rewrite (14) as:

$$I_{S_0} = e^{\frac{(\beta\sigma)^2}{2}} \iint_{S_0} \left[ R_1^m(x, y) Q \left( \beta\sigma + \frac{M_1 - M_0}{\sigma} \right) \kappa dA(x, y) \right] \quad (15)$$

$$Q(y) = \int_y^\infty \frac{e^{-x^2/2}}{\sqrt{2\pi}}$$

Compared to hard hand over case the inter cell interference from  $S_0$  is reduced because BTS 0 can power control the problematic users inside larger area. It is assumed that the average own cell interference remains equal to hard hand over case because on average same number of users is soft handed over to the neighboring base stations.

In addition to interference from  $S_0$  BTS 0 receives inter cell interference also from area out side of  $S_0$ . Let's denote this area as  $\bar{S}_0$ , complementary to  $S_0$ . In  $\bar{S}_0$  the output power of each mobile controlled by 'the better' of two closest base stations. Hence the interference by a mobile in  $\bar{S}_0$  to BTS 0 is always equal or less compared to hard handover case. By naming the two candidate soft hand over base stations as BTS i and BTS j so that they are the two closest BTS for a mobile at  $(x, y) \in \bar{S}_0$ . By definition BTS 0 are excluded from the set. Mathematically the total mean interference caused by mobiles in  $\bar{S}_0$  can be stated as:

$$I_{\bar{S}_0} = \iint_{S_0} \left[ R_i^m(x, y) E \left[ 10^{(\epsilon_i - \epsilon_0)/10}; r_i^m(x, y) 10^{\epsilon_i/10} < r_j^m(x, y) 10^{\epsilon_j/10} \right] \kappa dA(x, y) \right] + \iint_{\bar{S}_0} \left[ R_j^m(x, y) E \left[ 10^{(\epsilon_j - \epsilon_0)/10}; r_j^m(x, y) 10^{\epsilon_j/10} < r_i^m(x, y) 10^{\epsilon_i/10} \right] \kappa dA(x, y) \right] \quad (16)$$



which can be simplified to:

$$I_{s_0}^- = \iint_{s_0} 2 \left[ R_1^m Q \left( \frac{\beta\sigma}{2} + \frac{|M_1 - M_2|}{\sigma} \right) \right] \kappa dA \quad (17)$$

Thus relative interference from other cells,  $f$ , in soft hand over case is:

$$f = \frac{I_{s_0} + I_{s_0}^-}{k_u} = e^{(\beta\sigma)^2/2} \frac{2}{3\sqrt{3}} \left[ \iint_{s_0} R_1^m Q \left( \beta\sigma + \frac{M_1 - M_0}{\sigma} \right) dA + \iint_{s_0} 2 \left[ R_1^m Q \left( \frac{\beta\sigma}{2} + \frac{|M_1 - M_2|}{\sigma} \right) \right] dA \right] \quad (18)$$

The value of relative other cell interference is evaluated numerically for several  $M$  and  $\sigma$  and shown in Table 2.

$\sigma$ dB	$m=3$	$m=4$	$m=5$
0	0.77	0.44	0.30
4	0.87	0.65	0.31
8	1.60	0.77	0.47
12	5.93	2.62	1.42

Table 2. Inter cell interference ration in case of soft hand over . Table is obtained from [1].

Compared to Table 1, soft handover reduces greatly the other cell interference ratio. However same benefits can be reached by hard hand over as well if it is based on pathloss, as in GSM, and handover algorithm is fast enough compared to the fluctuations in the slow fading process.

## 5. SECTORED CELLS

Interference can be further reduced by sectored antennas. Effects of sectored cell can be analyzed by making the propagation model, Equation 7, to be dependent of angle of the incoming signal with respect to center of antenna cone. According to [1] this reduces interference by factor of 2.4.

## 6. ERLANG CAPACITY

Previously we have tried to answer the question: “How many user can be served by each base station in a seamless CDMA system.” Unfortunately, from the operator point of view, the user arrivals and departures are controlled by the user itself rather than by the operator. From the operator point of view individual call start and call end events are random. Therefore in this chapter we seek answer to somewhat more difficult question of outage probability: “What is the probability to have too many users simultaneously active in a base station. Given that we have statistical information of user behavior and information of how many users can be served by a base station.” According to studies [5] we can assume that users arrive to system according to Poisson Process with  $\lambda$  call starts/s by whole population and let the mean

holding time be exponentially distributed with average call duration of  $1/\mu$ . The occupancy (amount of on going phone calls) distribution can be modeled e.g. by lost call held Markov chain [5]. Then the probability that there are  $k$  calls active at given time is:

$$P_k = \frac{(\lambda/\mu)^k}{k!} e^{-\lambda/\mu} \quad (19)$$

Equation 19 is Erlang's first formula (B-formula) for infinite amount of servers.

Outage for **single cell** CDMA system is defining as event when there more active users in a cell than Equation 4 allows, mathematically:

$$P_{\text{out}} = P\left(\sum_{i=2}^{k_u} \varpi_i > K\right) \quad (20)$$

Where  $k_u$  is random variable with density distribution according to 19. And voice activity factor  $\varpi$  is Bernoulli distributed random variable with  $3/8$  probability to be 1 and  $5/8$  probability to be 0. Parameter  $K$  in Equation 20 is derived from the requirement that total interference + noise power received by a base station divided by background noise should be limited in order to keep network stable [1]. Hence total received interference +noise power denoted as  $I_0W$  is:

$$I_0W = \sum_{i=2}^{k_u} \varpi_i E_b R + N_o W \quad (21)$$

And let the interference+noise divided by noise ratio be less than 10, thus:

$$\frac{I_0}{N_o} < 10 \quad (22)$$

Substituting 22 to 21 and solving 21 for  $\varpi$  we obtain the parameter  $K$  in Equation 20.

$$P_{\text{out}} = P\left(\sum_{i=2}^{k_u} \varpi_i > \frac{W/R(1-1/10)}{E_b/I_0}\right) < P\left(\sum_{i=1}^{k_u} \varpi_i > \frac{W/R(1-1/10)}{E_b/I_0}\right) \quad (23)$$

Distribution of the left hand side of the inequality of Equation 23 can be derived by construction the generating function [10]:

$$e^{\sum_{i=1}^{k_u} \varpi_i} = e^{\left(\frac{\lambda \varpi}{\mu}(e^{\varpi}-1)\right)}$$

This is generating function for Poisson  $(\lambda \varpi/\mu)$  distribution [11], thus outage probability is the tail of Equation 19:

$$P_{\text{outage}} < \sum_{k=K}^{\infty} \frac{(\lambda \varpi/\mu)^k}{k!} e^{-\lambda/\mu} \quad (24)$$

Other cell interference can be included into 22 by arguing that other cell interference ratio is constant, thus summation in 20 is from 2 to  $k_u(1+f)$  instead of  $k_u$ . Thus 22 becomes:

$$P_{\text{outage}} < \sum_{k=K}^{\infty} \frac{(\lambda \bar{\omega}(1+f)/\mu)^k}{k!} e^{-\lambda \bar{\omega}(1+f)/\mu} \quad (25)$$

To obtain 25 we assume that  $k_u(1+f)$  is constant or can be rounded to constant with negligible effects.

## 7. ERLANG CAPACITY WITH IMPERFECT POWER CONTROL

The accuracy for reverse link power control is the most crucial issue for CDMA system capacity and for network stability. Imperfections in power control can be added to Equation 20 by arguing that the energy/bit received by base station from a user is not constant but varies log-normally. Then 20 can be written as:

$$P_{\text{out}} = P \left( \sum_{i=2}^{k_u(1+f)} \tau_i \bar{\omega}_i < K \right) \quad (26)$$

where  $\tau_i$  is lognormally distributed with mean value of 1 and std of  $\sigma$  and it is independent for each user. The distribution of the left hand side of the inequality of Equation 26 can not be solved analytically, at least the author can not, because the generating function does not converge. However mean and variance can be derived:

$$E \left( \sum_{i=2}^{k_u(1+f)} \tau \bar{\omega}_i \right) = \left( \frac{\lambda}{\mu} \right) (1+f) \bar{\omega} e^{(\beta\sigma)^2/2} \quad (27)$$

$$\text{Var} \left( \sum_{i=2}^{k_u(1+f)} \tau \bar{\omega}_i \right) = \left( \frac{\lambda}{\mu} \right) (1+f) \bar{\omega} e^{2(\beta\sigma)^2}$$

Thus a normal approximation can be made. In Figure 3 normal approximation of uplink capacity is presented for IS- 95 and for WCDMA. The used user bit rate is 8 kbps and required  $E_b/N_o$  is 6.5 dB for both systems. The amount is users is the average amount of simultaneously active users ( $\lambda/\mu$ ) of the traffic model described above.

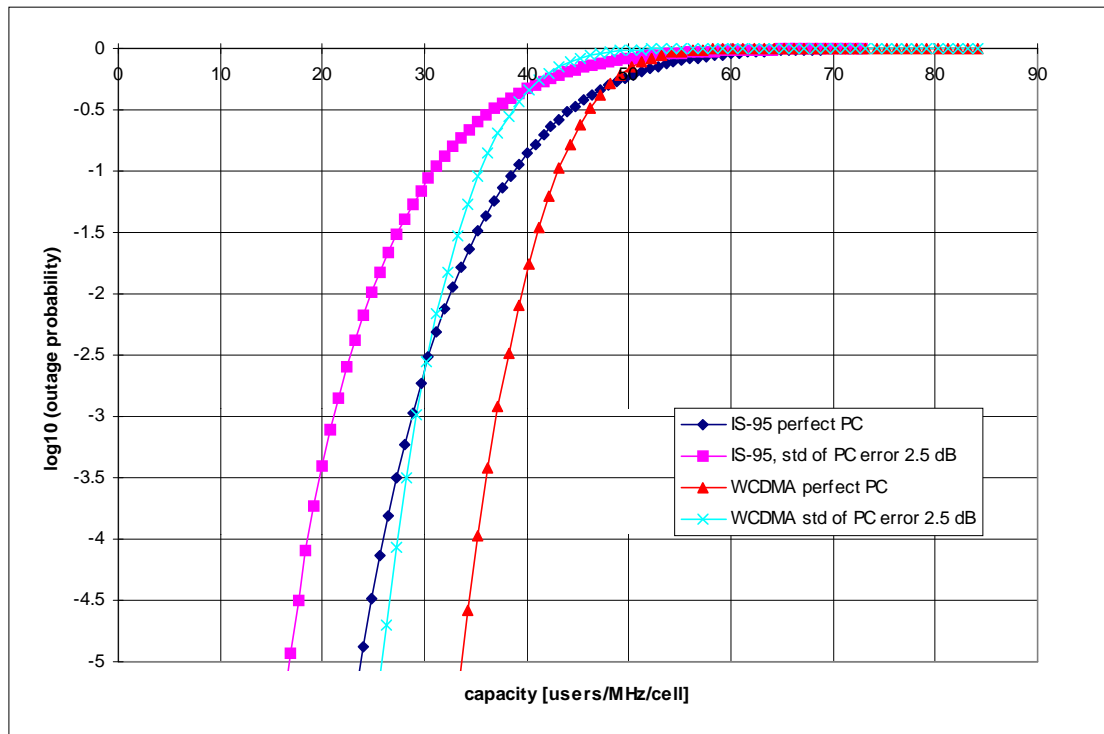


Figure 3. Gaussian approximations of uplink capacities for IS-95 and for WCDMA.

## 8. ERLANG CAPACITY OF DOWNLINK (FORWARD LINK)

From the system capacity analysis point of view there are five significant differences in downlink compared to uplink. Firstly communication is from one transmitter to several receivers. This implies that propagation conditions of own cell interference is identical to own signal, thus fast power control is not crucial. Secondly in case of soft hand over, interference may be increased because the information is transmitted simultaneously from several base stations. Thirdly interference is received from few large stationary spots rather than many distributed small sources. Fourthly closed loop power control commands for uplink reduce capacity. Fifthly by sacrificing part of the downlink resources to pilot symbols, synchronization and coherent detection can be facilitated, which enables to achieve gain from orthogonal codes.

Based on above the downlink capacity problem can be seen as the following constrained maximization problem: “Maximize the average number of simultaneously served users in a base station given that each base station has maximum total output power and each user must meet required  $E_b/I_0$  target at least with probability of  $(1-\chi)$ .” Mathematically the above sentence for hard hand over and non-orthogonal codes can be expressed as:

$$\begin{aligned} & \sum_{i=1}^k \phi_i \leq 1 \\ & P \left( \left( \frac{E_b}{I_0} \right)_i \leq \frac{\beta \phi_i S_{ij} (W/R)}{\left( \sum_{j=1}^J S_{ji} + N_0 W \right)} \right) < \chi \end{aligned} \quad (28)$$

where  $\phi_i$  is the ratio of total output power (normalized to unity) allocated to  $i^{\text{th}}$  user.  $(1-\beta)$  is ratio of total output power allocated to pilot,  $J$  is amount of base station that have notable effect on other cell interference and  $S_{ji}$  is total received power by mobile  $i$  from base station  $j$ . By assuming that all users have same  $E_b/I_0$  target the inequality in latter constraint of Equation 28 can be replaced by equality and be solved for  $\phi_i$ , which can then be substituted to first constraint in 28. This leads to outage definition similar to 23.

$$P_{\text{out}} = P \left( \sum_{i=1}^{k_u} \varpi_i \left( 1 + \sum_{j=2}^J \frac{S_{ji}}{S_{ii}} + N_0 W / S_{ii} \right) \frac{E_b/I_0}{W/R \cdot \beta} > 1 \right) \quad (29)$$

where the own cell is marked as 1. Soft handover can be included into 29 by arguing that the ratio of mobiles in soft hand over ( $g$ ) is network planning parameter, thus controllable by the network operator. Then the amount of simultaneously users are increased by factor  $g$ :

$$P_{\text{out}} = P \left( \sum_{i=1}^{k_u(1+g)} \varpi_i \left( 1 + \sum_{j=2}^J \frac{S_{ji}}{S_{ii}} + N_0 W / S_{ii} \right) \frac{E_b/I_0}{W/R \cdot \beta} > 1 \right) \quad (30)$$

where  $g$  is derived so that mobiles in soft handover with more than two base stations are weighted accordingly. Thus if all mobile are in soft hand over with 3 base stations,  $g$  equals two. If orthogonal codes are used, own cell interference is partly canceled. Then the latter constraint in 28 becomes:

$$P \left( \left( \frac{E_b}{I_0} \right)_i \leq \frac{\beta \phi_i S_{ij} (W/R)}{\left( \sum_{j=1}^J h_j S_{ji} + N_0 W \right)} \right) < \chi$$

where  $h_j$  is the cancellation factor,  $0 < h_j < 1$  if  $j=1$  and zero otherwise. With orthogonal codes the outage probability reduces to:

$$P_{\text{out}} = P \left( \sum_{i=2}^{k_u(1+g)} \varpi_i \left( h + \sum_{j=2}^J \frac{S_{ji}}{S_{ii}} + N_0 W / S_{ii} \right) \frac{E_b/I_0}{W/R \cdot \beta} > 1 \right) \quad (31)$$

The effects of the uplink closed loop power control commands can be taken into account by adding the information bit rate  $R$  and voice activity statistics  $\varpi$ . Also  $E_b/I_0$  target might be higher for power control commands.

$$R = R_{\text{user bits}} + R_{\text{PC bits}}$$

$$\varpi = \begin{cases} 1 & \text{with probability } 3/8 \\ R_{\text{PC bits}} / R_{\text{total}} & \text{with probability } 5/8 \end{cases}$$

According to [1] if one compares Chernoff bounds of Equations 26 and 31. Downlink has better capacity provided that  $h < 0.5$  and  $g < f$  if IS-95 parameters are used.

## 9. SIMULATIONS

In the simulations part of this document some alternative environment and services compared to speech service in hexagonal environment are presented. In addition brief summary of the principles of both static and dynamic CDMA simulations are given.

### 9.1 Environments

Hexagonal cell layout as shown in Figure 1 is most widely used simulation environment. Lately the interest has shifted more to urban city environments and indoor environments. For urban simulations a Manhattan type of city is often used, see Figure 3. In Manhattan environment it is assumed that buildings are very high and signals attenuation is calculated street wise, if all users are outdoors. There are two characteristic points that separate Manhattan from normal hexagonal environment:

1. Received signal strength decreases stepwise as line-of sight is lost between BTS and mobile and afterward signal attenuation exponent increases. As an example pathloss increases with exponent 2 while in line-of-sight, when line-of-sight is lost attenuation increases 15 dB very rapidly and afterward pathloss increases with exponent 4.
2. There are places where interference level is significantly higher, usually at street junctions.

Indoor environments are usually either office and residential. An example of a floor in office environment is shown in Figure 4. Typically there are at least 3 floors, thus indoor office simulations are often 3D simulations. Layouts of Figures 3 and 4 have been used in ETSI evaluation process for 3rd generation radio interface. More detailed information of test environments can be found in [12]. The figures are also published in [12].

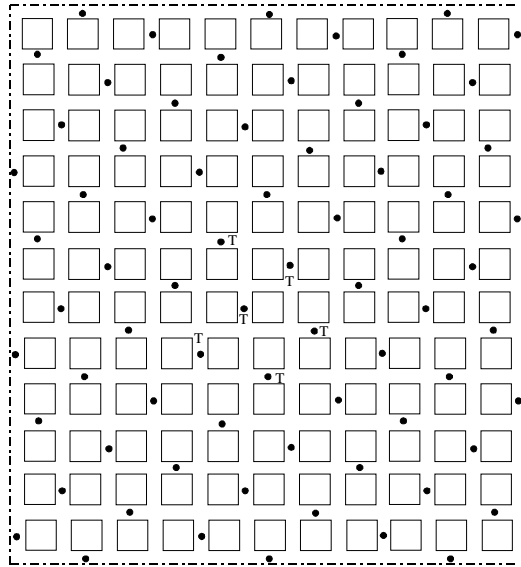


Figure 3. Example layout of Manhattan environment. Figure is obtained from [12].

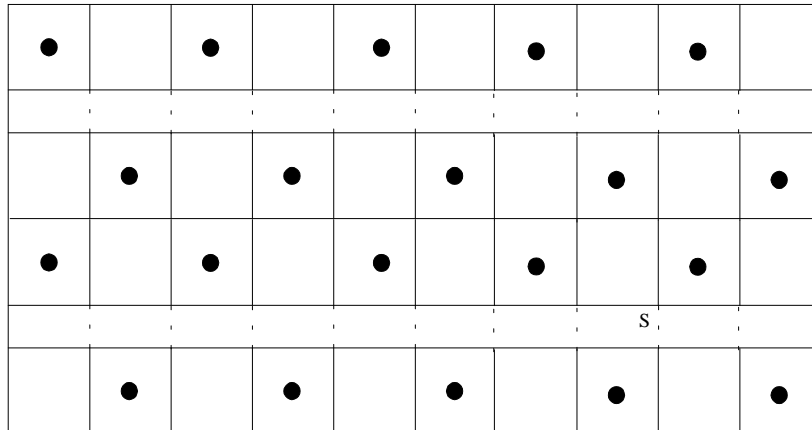


Figure 4. Example layout of one floor in indoor office environment. Figure is obtained from [12].

## 9.2 Services

In the analysis part of this document the speech service was analyzed. If data serviced were analyzed or simulated somewhat different assumption should be made. In case of circuit switched data things are not that different from speech, some differences however exists:

1. Data flow is usually constant, thus 'voice activity' is always 1.
2. Usually smaller BER is tolerate thus  $E_b/I_0$  target is higher, however not so strict delay requirement may compensate this.
3. As bit rates become higher, system might became (orthogonal) code limited

Thus for low bit rate data services, the above analysis can be repeated straightforward. In case of higher bit rate the addition constraint for limited amount of orthogonal codes must be added. In case of packet switched data differences are severe, because after tight delay requirements don't exist, it is not necessary to fulfill  $E_b/I_0$  target all the time.

### 9.3 Static simulations

A widely used static method to simulate CDMA network is snapshot approach. However because fast power control has crucial importance in CDMA system, the simulation ought not to be completely static, but the power control procedure should be included into simulation. Typical flow of static CDMA simulations is following:

1. Select environment, service and needed parameters
2. Place the amount of mobiles given by the traffic model in network according to selected user distribution statistics.
3. Select serving base station(s) and set initial output powers
4. Run power control algorithm for e.g. 100 ms to stabilize powers.
5. Run power control algorithm and channel fading model for e.g. 500 ms. Record the average  $I_0/N_0$  over the 500 ms for each user.
6. Calculate the ratio of users ( $R$ ) who did not fulfill the average  $I_0/N_0$  target.
7. Repeat steps 2 to 6  $N$  times to get vector  $\mathbf{R} = [R_1 \dots R_N]$ .
8. Calculate average  $\mathbf{R}$ , which is outage probability with parameters given in step 1.

To compare static simulations and analysis presented above. In [4] uplink simulation results for circuit switched 74.3 kbps data service is given. Used bandwidth is 5.12 MHz, no Poisson arrival exponential holding time model has been used, hence comparison must be done to Equation 13. The intercell interference factor  $f$  is simulated to be 0.37. If the soft handover analysis were done for three base station,  $f$  would be 0.49 in case the simulation propagation parameters:  $m=3.6$  and slow fading has std of 3.6 dB. Obtained spectrum efficiencies are presented in Table 3. In third column it is assumed that in addition to results obtained by Equation 13, 25% of resources are reserved for fluctuations in soft handover.



	<i>Spectrum efficiency [users/MHz/cell]</i>	<i>Spectrum efficiency with 25% soft HO margin</i>
Simulated	2.3	2.3
Analytical, f=0.36	3.52	2.8
Analytical, f=0.49	3.24	2.6

*Table 3. Comparison of analytical and static simulated CDMA capacities.*

#### **9.4 Dynamic simulations**

Dynamic simulations allow to study system capacity from the wider point of view. As an example consider users moving in Manhattan environment. Let's suppose that the inter cell interference is very small, expect for users in street crossing very it is very high. If static simulation approach is used with evenly distributed users to streets, the outage probability will be dependent on the area of the crossing divided by total street area, thus spectrum efficiency is determined by the block size and street width ratio. The same applies also if analysis is used. If dynamic simulation tool is used, most of the users will be at a crossing sometime during the call. Also dynamic simulation are good to study capacity of service that have variable bit rate, e.g. packet data.

In addition to capacity analysis, simulations are used to study the performance and parametrization of a single radio resource control algorithm. In such cases dynamic simulations have clear advantage over static simulations. In the dynamic simulations, the dynamic network behaviors of the actions of a single connection can be analyzed and in addition the data measurement are signaling performed by mobile and base station with its errors and delay can be better modeled. The drawback of dynamic simulations is long simulation times, because several base stations must be included into network in order to get reliable intracell distribution.

#### **10. CONCLUSION**

CDMA system capacity can be derived analytically quite accurately if:

1. Simple cell layout is used
2. Simple traffic model is propitiate, which is true for speech service but not necessary for packet data services.
3. The amount of users per carrier, parameter N must by sufficiently large to justify the assumption of evenly distributed users. Especially if soft handover is used.

However, the introduction of following phenomena and network structures makes the analysis without significant approximations very difficult, thus simulations are more accurate.

- Variation of intercell interference due to fast power control that tries to track channel fading.
- Non uniform traffic distribution and mixture of services.
- Hierarchical cell structures (HCS), where e.g. micro cellular and macro cellular networks co-exists in same area.
- Services that have variable bit rate due to e.g. automatic repeat requests (ARQ) for packet data services.
- Delays and hysteresis marginal in hard and soft handover.
- High bit rate services

Meaningful comparison of simulated capacity figures of e.g. GSM and IS-95 or WCDMA, WB-TDMA [8] and hybrid C/TDMA [9] requires first a comprehensive analysis of simulation assumptions, thus it is not included into this document.

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