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Cellular Architectures in CDMA Network

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1 INTRODUCTION

Code Division Multiple Access (CDMA) is a well-known radio communication technique to allow multiple users to share the same spectrum simultaneously. It is an alternative to frequency-division and time-division multiple access. Its advantages include higher spectral reuse efficiency, greater immunity to multipath fading, better and simpler exploitation of sectorisation and and voice inactivity and more robust handoff procedures.

In a traditional CDMA digital communication system, the voice signal is encoded into a digital stream using a speech coder (e.g. AMR, EVRC). Forward error correction is utilized, adding redundant bits to the speech data. The data will also be interleaved to combat error bursts occurring due to the multipath propagation. After the aforementioned steps, the data stream is multiplied by the spreading code, which replaces the data with a sequence of code chips. One chip is defined as the period of the spreading code. Hence, the spreading process consists of replacing each bit in the original data sequence with the complete spreading code word. The chip rate is much higher than the data rate hence causing the bandwidth of the user data to be spread.

At the receiver the composite signal containing the spread data from multiple users is multiplied by a synchronized version of the spreading code for the wanted user. The autocorrelation properties of the codes will allow the receiver to identify each delayed replica of the transmitted signal, provided that the signals are separated by more than one chip period and the receiver has the capability of tracking each significant path. This is achieved using a RAKE receiver that can process multiple delayed received signals. Coherent combination of these replicas allows the recovery of the user’s original signal. The unwanted signals remain wideband (with a bandwidth equal to that of the spread signal) and appear as noise with respect to the wanted signal. Since the bandwidth of the despread wanted signal is reduced relative to this noise, the signal-to-noise ratio of the wanted signal is enhanced by the despreading process in proportion to the ratio of the bandwidths. The bandwidth ratio is equal to the ratio of the chip rate to data rate and is known as the processing gain. For this process to work, all user signals should be received at or near the same power at the receiver. Therefore, the CDMA systems must use power control on the uplink; otherwise, the link performance will suffer from the near-far effect, a condition where the transmissions received from distant mobiles experience excessive interference from nearby mobiles. The IS-95 and WCDMA uplinks employ both a fast closed-loop power control algorithm to combat variations in the received signal power due to path loss, shadowing, and fast envelope fading (at low Doppler frequencies). In cdma2000 and WCDMA the fast closed-loop power control algorithm is extended to cover also the downlink. In the IS-95 and cdma2000 systems the frequency of the power control is 800 Hz, while in WCDMA it is 1500 Hz.
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 codes. For such systems, multiple-access interference from neighboring cells must be carefully accounted for. The propagation path loss associated with these interfering signals is relatively small compared to those found in narrow-band and mid-band TDMA systems that employ frequency reuse plans.

With cellular CDMA systems, any technique that reduces multiple-access interference translates into a capacity gain. Such techniques include, for example, voice activity detection, cell sectoring, adaptive antennas, multi-user detection and interference cancellation.

The CDMA maximum capacity is typically “soft-limited”, meaning that the capacity is typically a trade-off between coverage and quality, see Figure 1. Thus, the maximum number of users can be increased, if the system coverage is decreased, or the service quality is lowered.

![Quality Triangle](image)

**Figure 1.** CDMA capacity is typically a trade-off between coverage and quality.

Numerous analytical ways to define the CDMA capacity, in particular the CDMA uplink capacity, can be found in the literature, for example in [1]. For IS-95, the general assumption has been that the system capacity is uplink-limited. However, in 3G systems, such as WCDMA and cdma2000, the services will most probably be more and more asymmetrical, so that in many cases the downlink will offer a higher bit rate than the uplink. Therefore, the question about the CDMA downlink capacity has become extremely interesting during the last few years.

The downside in many analytical approaches has been that they are relatively complex, and/or do not take all the significant aspects into account. Therefore, in this paper, a slightly different approach is chosen. Here, the overall capacity approximations are based on general CDMA theory, but results from simple system simulations are utilized as an input instead of possibly tedious analytical calculations.
The structure of the rest of this paper is the following: First, a brief presentation of the bit error probability with the RAKE reception is given. Then, the issue about the CDMA uplink and downlink capacity is discussed more thoroughly.

Finally, it should be noted that the approach presented in this paper is primarily valid only for circuit switched services, such as speech and real-time data.

### 2.1 Error Probability with the RAKE Reception

Assume a RAKE receiver with perfect channel estimation. Then, with coherent BPSK or QPSK signaling the bit error probability conditioned on $\gamma_b$ is

\[ P_b(\gamma_b) = \frac{1}{2} \text{erfc}(\sqrt{\gamma_b}) = Q(\sqrt{2\gamma_b}) \]  

(2.1)

where the signal-to-noise ratio (SNR) per bit $\gamma_b$ is given as

\[ \gamma_b = \frac{\varepsilon}{N_0} \sum_{k=1}^{L} \alpha_k^2 = \sum_{k=1}^{L} \gamma_k \]  

(2.2)

where $\gamma_k = \varepsilon \alpha_k^2 / N_0$ is the instantaneous SNR on the $k$th channel. In the above, the number of channels is assumed to be equal to $L$, $\varepsilon$ is the transmitted signal power, $\{\alpha_k\}$ represent the channel attenuations and $N_0$ is the noise power. Finally, the BEP can be written as

\[ P_b = \left(1 - \mu\right)^L \sum_{k=0}^{L-1} \binom{L-1+k}{k} \left(\frac{1+\mu}{2}\right)^k \]  

(2.3)

where

\[ \mu = \sqrt{\bar{\gamma}_k} \]  

(2.4)

and

\[ \bar{\gamma}_k = \frac{\varepsilon}{N_0} E(\alpha_k^2) \]  

(2.5)

is the average signal-to-noise ratio (SNR) for the $k$th path.

For binary, orthogonal FSK the conditional probability of error is
and finally, the BEP is the same as (2.3), but now

\[ \mu = \frac{\gamma_k}{2 + \gamma_k} \]  \hspace{1cm} (2.7)

Also in [2] the probability of error is derived for binary antipodal and orthogonal signals under the condition that the mean-square values are distinct. For such signals the conditional error probability can be written as

\[ P_2(\gamma_b) = \frac{1}{2} \text{erfc} \left( \frac{\gamma_b}{\sqrt{2}} \right) = Q \left( \sqrt{\frac{\gamma_b}{2}} \right) \] \hspace{1cm} (2.8)

where \( \rho_r = -1 \) for antipodal signals, \( \rho_r = 0 \) for orthogonal signals. This time, the error probability becomes

\[ P_2 = \frac{1}{2} \sum_{k=1}^{L} \pi_k \left[ 1 - \frac{\gamma_k (1 - \rho_r)}{2 + \gamma_k (1 - \rho_r)} \right] \] \hspace{1cm} (2.9)

where

\[ \pi_k = \prod_{j=1, j \neq k}^{L} \frac{\gamma_k}{\gamma_k - \gamma_j} \] \hspace{1cm} (2.10)

Perfect channel estimation is assumed in all cases presented above. In case of imperfect channel estimates, the error probabilities have to be modified accordingly, see for example [2].

### 2.2 CDMA UPLINK CAPACITY

A key element to the CDMA uplink capacity estimation is the interference rise above thermal noise ("noise rise") measured at the base station. In general, the total uplink interference consists of the power received from the mobiles connected to the base station in question (intracell interference, \( I_{hc} \)), power received from the mobiles connected to all the other base stations in the system (intercell interference, \( I_{oc} \)) and thermal noise (\( N \)), see Figure 2. In reality, also the interference from other CDMA carriers and co-existing cellular systems should be taken into account when estimating the total uplink interference. However, the impact of inter-carrier and inter-system interference is not considered here.
In CDMA uplink, a SIR-based fast closed loop power control is deployed. Furthermore, an additional outer loop power control tries to maintain the link quality (e.g., Block Error Rate, BLER) at the wanted level by adjusting the SIR target for the inner loop.

Assuming that user $i$ has a SIR target equal to $(E_b/N_0)$ and the bit rate equal to $R_i$, the received carrier power can be calculated in the following way

$$C_i = \left( \frac{E_b}{N_0} \right)_i \cdot \frac{R_i}{W} \cdot (I_{\text{tot}} - C_i) \quad \Rightarrow \quad C_i = \frac{I_{\text{tot}}}{1 + \frac{W/R_i}{(E_b/N_0)_i}}$$

(2.11)

where $W$ is the chip rate. Now, assuming an average of $M$ users per cell and an activity factor $\nu_i$, the total intracell interference becomes

$$I_{hc} = \sum_{i=1}^{M} C_i = I_{\text{tot}} \sum_{i=1}^{M} \frac{\nu_i}{1 + \frac{W/R_i}{(E_b/N_0)_i}}$$

(2.12)

The intercell interference can be taken into account with the help of the “frequency reuse factor”, $f$, which is defined as

$$f = \frac{I_{hc}}{I_{hc} + I_{oc}}$$

(2.13)

Taking the above into account, the total uplink interference can be written as
\[ I_{\text{tot}} = I_{\text{bc}} + I_{\text{oc}} + N = \sum_{f=1}^{M} \frac{v_i}{1 + \frac{W/R_i}{(E_b/N_0)}} + N \] (2.14)

Finally, the CDMA uplink noise rise can be solved as

\[ NR = \frac{I_{\text{tot}}}{N} = \frac{1}{1 - \frac{1}{f} \sum_{f=1}^{M} \frac{v_i}{1 + \frac{W/R_i}{(E_b/N_0)}}} = \frac{1}{1 - \eta} \] (2.15)

where \( \eta \) is the relative uplink cell load. The required \((E_b/N_0)_i\) can be derived from link simulations or from measurements. It should include the effect of the closed loop power control and the soft handover with realistic performance characteristics. The effect of the soft handover is measured as the macro diversity combining gain relative to the single link \(E_b/N_0\) requirement. The frequency reuse factor \( f \) is found to depend on the propagation conditions, shadow fading, antenna pattern as well as on the user distribution, see for example [3], [4], [5] and [6]. On top of that, the fast uplink power control together with the soft handover will have an impact on the \( f \) and \((E_b/N_0)_i\) as explained in [7] and [8], see also Chapter 2.2.1. Finally, since both the user distribution and the number of active users are dynamically changing, the frequency reuse factor will not stay constant as a function of time. However, during the system planning phase, an estimated average \( f \) factor is applied for each sector.

In Figure 3 the uplink noise rise as a function of the relative uplink load is shown. Typically, in order to secure the uplink stability, the systems are planned so that the maximum (average) noise rise is in the order of 3-6 dB, i.e. the maximum relative load

\[ \text{Figure 3. Uplink noise rise as a function of the relative load.} \]
level is 50-75%. Assuming a single service system, and that all users have the same (average) $E_b/N_0$ and activity factor,

$$\eta = \frac{\nu}{f} \frac{M}{1 + \frac{W/R}{E_b/N_0}} = \frac{M}{M_{pole}}$$  \hspace{1cm} (2.16)

Thus, at the planned maximum load level $\eta_0$, each sector can serve an average of $M_{max}$ users, where

$$M_{max} = \eta_0 \frac{f}{\nu} \left(1 + \frac{W/R}{E_b/N_0}\right)$$  \hspace{1cm} (2.17)

In reality, the frequency reuse factor will vary due to the dynamical behavior of the mobile users. This can be seen also from Figure 4, where the simulated uplink noise rise is presented as a function of the average number of users per cell for 12.2 kbps and 128 kbps services. The users are assumed to be uniformly distributed (in average) over the whole system area. Thus, the momentary number of active users connected to a certain cell can vary. In Figure 5, the distribution of the simulated momentary frequency reuse values is shown.

![Figure 4](image-url)

**Figure 4.** Simulated uplink noise rise as a function of the average number of active users per cell. The dashed curves correspond to different percentiles of the simulated noise rise values.
2.2.1 The Impact of Fast Power Control and Soft Handover

Assuming an ideal power control, the impact of fast power control can be studied in the following manner [7]:

The instantaneous transmit power of the mobile station is denoted by $p_t$. In case of an ideal power control the $p_t$ is set so that the received bit-energy to interference spectral density $E_b/I_0$ is at constant level just ensuring the desired quality. Here it is assumed that the interference (interuser interference + noise) is close to additive white Gaussian noise (AWGN), which is a reasonable assumption in a CDMA.

The ideal power control equation can be written as

$$G \frac{p_t X}{I} = \rho$$  \hspace{1cm} (2.18)

where $I$ is the interference power at the base station, $G$ is the processing gain, $\rho$ is the required $E_b/I_0$ ratio and $X$ is the instantaneous channel gain varying under multipath conditions. It can be assumed that the expectation value of $X$ is one, $E(X) = 1$, since only fast power control effects are studied here. As the power control keeps the $E_b/I_0$ constant, the $p_t$ can be solved from (2.18):

$$p_t = \frac{\rho I}{G} \cdot \frac{1}{X}$$  \hspace{1cm} (2.19)

Thus, the statistics of the transmit power is the statistics of the inverse channel gain $Y$, $Y = 1/X$. Next, the expectation value of $Y$ is calculated in some special cases. This is called the average transmit power increase caused by the fast power control.
It is assumed that the signal is received by an ideal RAKE receiver using ideal maximum ratio combining of $L$ multipaths. Then $X$ and its probability density function $f_X$ can be written as [2]

$$X = X_1 + \ldots + X_L \quad E(X_k) = \bar{T}_k, \quad k = 1, \ldots, L$$

$$f_X(x) = \sum_{k=1}^{L} \frac{\pi_k}{\bar{T}_k} e^{-x/\bar{T}_k} \quad \pi_k = \prod_{j=1, j \neq k}^{L} \frac{\bar{T}_k}{\bar{T}_j}$$

(2.20)

In case of two Rayleigh fading paths ($L = 2$), and assuming that $a$ is the ratio of the powers of the two paths, the pdf of $X$ becomes

$$f_X(x) = \frac{a+1}{a-1} \left[ e^{-x(1+1/a)} - e^{-x(1+a)} \right]$$

(2.21)

and the average transmit power increase

$$E(Y) = \frac{a+1}{a-1} \ln(a)$$

(2.22)

If two multipaths and antenna diversity with uncorrelated antennas is considered then the result is effectively four paths and the corresponding pdf and the average transmit power increase are

$$f_X(x) = 4 \left( \frac{a+1}{a-1} \right)^2 \left[ e^{-2(1+a)x} \left( x - \frac{a}{1-a^2} \right) + e^{-2(1+1/a)x} \left( x + \frac{a}{1-a^2} \right) \right]$$

(2.23)

$$E(Y) = 2 \left( \frac{a+1}{a-1} \right)^2 - 4 \frac{a + a^2}{(a-1)^3} \ln(a)$$

(2.24)

In Figure 6 the theoretical average transmit power increase with ideal power control has been shown as a function of the average power difference of the two propagation paths.
The theoretical transmit power increase as a function of the average power difference of the two propagation paths.

The impact of the transmit power increase on the uplink capacity can be estimated in the following way: Assume that the frequency reuse factor without fast power control is $f_{nuopc}$. With fast power control, the received power from the users belonging to the own cell $I_{hc}$ does not change, but the total received power from the users belonging to the other cells $I_{oc}$ increases with the amount given above.

Assuming that the $I_{oc}$ with fast power control is defined as

$$I_{oc,pc} = I_{oc,nopc} \cdot 10^{T/10}$$  \hspace{1cm} (2.25)

the frequency reuse factor with the fast power control becomes

$$f_{pc} = \frac{I_{hc}}{I_{hc} + I_{oc,pc}} = \frac{1}{1 + \left( \frac{1}{10^{f_{nopc}T/10}} - 1 \right)} \cdot 10^{T/10}$$  \hspace{1cm} (2.26)

where $T$ is the average transmit power increase given in desibels.

When the mobile is in soft handover, it will experience two different kinds of macro diversity combining gains. Firstly, the required Rx $E_b/N_0$ will become lower due to the fact that the RNC can select the best received frame from all the RBS within the active set on a frame-by-frame basis. Secondly, the average transmit power increase is reduced, since the fast power control does not anymore have to compensate for the deepest fades.

In Figure 7 the macro diversity combining gain in Rx $E_b/N_0$ is presented for the Pedestrian A and Vehicular A channels with 2-branch Rx diversity and different user
velocities. The gain in average transmit power is shown in Figure 8. The curves are simulated for 12.2 kbps speech service with 20 ms interleaving depth. Furthermore, the outer loop BLER target is set to 0.7%. Finally, the fast power control is assumed to have the following imperfections:

- Power control rate = 1500 Hz
- Step size = 1 dB
- Standard deviation for the SIR estimation error = 3 dB
- TPC delay = 2 slots
- TPC bit error probability = 4%

Figure 7. Macro diversity combining gain in Rx $E_b/N_0$ for the Pedestrian A and Vehicular A channels.

Figure 8. Macro diversity combining gain in the average transmit power for the Pedestrian A and Vehicular A channels.
As can be noticed, the macro diversity gains are larger for the Pedestrian A channel than for the Vehicular A channel. This is natural, because the Pedestrian A channel has less multipath diversity, see Figure 9. Furthermore, one can notice that there are almost no macro diversity combining gain left when the secondary link is 6-10 dB weaker than the primary link.

![Pedestrian A and Vehicular A channel profiles.](image)

**Figure 9. Pedestrian A and Vehicular A channel profiles.**

The limitation in the results given above is that they are not directly applicable for the CDMA uplink capacity estimation. The reason is that for the $M_{pole}$, the sum of all users is required. Now, only the users which are in soft handover experience any macro diversity combining gain, while all the others do not. Furthermore, in case of softer handover (handover between two sectors belonging to the same site) maximum ratio combining is applied instead of the selection combining.

![Three sector cell plan.](image)

**Figure 10. Three sector cell plan.**
In order to take also these aspects into account, a set of system simulations is run. There, the main assumption is a 3-sector cell deployment, see Figure 10. The environment is assumed to be urban, with the distance dependent part of the path loss equal to [9]

\[ L = 15.3 + 37.6 \cdot \log(d) \]  

(2.27)

where \( d \) is the distance between the transmitter and the receiver given in [m]. On top of \( L \), a log-normally distributed shadow fading gain with 8 dB standard deviation is added.

The results are shown in Table 1. As a reference, the frequency reuse factor without fast power control and soft handover for the assumed environment is approximately 0.62. As expected, the macro diversity gain is clearly larger for the Pedestrian A channel than for the Vehicular A channel. Furthermore, from the system capacity point of view, the soft handover gains become quite modest compared to the values shown in Figure 7 and Figure 8.

<table>
<thead>
<tr>
<th>Maximum Doppler Frequency</th>
<th>Pedestrian A No Soft Handover</th>
<th>Pedestrian A AS size = 2 Margin = 3 dB</th>
<th>Vehicular A AS size = 2 Margin = 3 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Tx power incr.</td>
<td>Frequency reuse factor</td>
<td>Gain in Rx ( E_b/N_0 (dB) )</td>
</tr>
<tr>
<td>5 Hz</td>
<td>2.0 dB</td>
<td>0.51</td>
<td>0.28</td>
</tr>
<tr>
<td>20 Hz</td>
<td>1.7 dB</td>
<td>0.52</td>
<td>0.35</td>
</tr>
<tr>
<td>40 Hz</td>
<td>1.2 dB</td>
<td>0.55</td>
<td>0.35</td>
</tr>
<tr>
<td>100 Hz</td>
<td>0.5 dB</td>
<td>0.59</td>
<td>0.32</td>
</tr>
<tr>
<td>250 Hz</td>
<td>0.2 dB</td>
<td>0.61</td>
<td>0.26</td>
</tr>
</tbody>
</table>

### 2.2.2 Soft Capacity

In FDMA and TDMA systems user blocking occurs, when all frequency slots or time slots have been allocated to users. In CDMA systems, users all share a common spectral frequency allocation over the time that they are active. Hence, new users can be accepted as long as there are receiver-processors to serve them, independent of time and frequency allocations. Assuming that a sufficient number of such processors is always available, the blocking in CDMA systems can be defined to occur when the interference level, due primarily to other user activity, reaches a predetermined level above the background noise level of mainly thermal origin [10]. While this noise rise could, in principle, be made arbitrarily large, after a certain level (about 10 dB nominally), the interference increase per additional user grows very rapidly, yielding diminishing returns and potentially leading to instability.

Assume first that the admission control in a single service CDMA system is based on uplink interference. Hence, new users will be blocked when \( NR \geq NR_{th} \) where \( NR_{th} \) is the
predefined noise rise threshold for the admission control. Then, the uplink capacity in terms of the number of available channels can be solved as

\[
M = \frac{f}{v} \left( 1 + \frac{W}{R} \cdot 10^{\frac{E_b/N_0}{10}} \right) \left( 1 - 10^{\frac{-NR_{th}}{10}} \right)
\]  

(2.28)

where the noise rise \( NR \) and \( E_b/N_0 \) are given in dB. Actually, already the value for \( M \) is “soft-limited”. This is due to the fact that new users can be admitted into the system, if the quality of the already admitted users is slightly reduced. This can be done by allowing a higher \( NR_{th} \) for the admission control, or by reducing the Rx \( E_b/N_0 \) for some of the users.

Next, the Erlang capacity of the CDMA uplink is briefly discussed. If the capacity is hard blocked, i.e. limited by the amount of hardware, the Erlang capacity can be obtained from the Erlang-B model. Thus,

\[
B(\rho, m) = \frac{\rho^m}{m! \sum_{k=0}^{m} \frac{\rho^k}{k!}}
\]  

(2.29)

where \( B(\rho, m) \) is the blocking probability, \( m \) is the total number of channels in the cell, and \( \rho = \lambda \mu \) is the total offered traffic within the cell (\( \lambda \) is the call arrival rate and \( \mu \) is the mean call duration).

If the maximum capacity is limited by the amount of interference in the air interface, it is by definition a soft capacity, since there is no single fixed value for the maximum capacity. Therefore, the Erlang-B formula is not applicable, since it would give too pessimistic results. The total channel pool is larger than just the average number of channels per cell \( M \), since the adjacent cells share part of the same interference, and therefore more traffic can be served with the same blocking probability.

The soft capacity can be explained in the following way. The less interference is coming from the surrounding cells, the more capacity is available in the middle cell. With a low number of channels per cell, i.e. in case of high bit rate users, the average loading must be quite low in order to guarantee low blocking probability. Since the average loading is low, there is typically extra capacity available in the neighboring cells. This capacity can be typically borrowed from the adjacent cells. Therefore, the interference sharing gives soft capacity.

In the following calculations it is assumed that the number of subscribers is the same in all cells, but the connections start and end independently. In addition, the call arrival rate follows the Poisson distribution. There is an additional soft capacity available if also the number of users in the neighboring cells is smaller.
Uplink soft capacity can be approximated based on the total interference at the base station. This interference consists of both intracell and intercell interference. Therefore, the total channel pool can be obtained by dividing the average number of channels per cell, \( M \), with \( f \). This total interference corresponds to a single cell capacity. The basic Erlang-B formula is applied to this larger channel pool. The obtained Erlang capacity is then equally shared between the cells (multiplied by \( f \)) [11].

### 2.2.3 Uplink Soft Capacity Example

In this chapter, a simple example is given in order to visualize the soft capacity in the CDMA uplink. This is done via simple calculations. Throughout the example, a number of assumptions are applied. These are listed in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumed Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>User bit rate</td>
<td>Speech: 12.2 kbps</td>
</tr>
<tr>
<td></td>
<td>Real-time data: 16, 32, 64, 128 kbps</td>
</tr>
<tr>
<td>Activity factor</td>
<td>Speech: 0.67</td>
</tr>
<tr>
<td></td>
<td>Real-time data: 1</td>
</tr>
<tr>
<td>( E_b/N_0 )</td>
<td>Speech: 5 dB</td>
</tr>
<tr>
<td></td>
<td>Real-time data: 3 dB</td>
</tr>
<tr>
<td>( f )</td>
<td>0.59</td>
</tr>
<tr>
<td>Noise rise threshold</td>
<td>4 dB (60% load)</td>
</tr>
<tr>
<td>Blocking probability</td>
<td>2%</td>
</tr>
</tbody>
</table>

### Table 3. Soft Capacity Gain

<table>
<thead>
<tr>
<th>Service</th>
<th>Number of channels</th>
<th>Hard blocking</th>
<th>Soft blocking</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.2 kbps</td>
<td>53.3</td>
<td>43.3</td>
<td>46.4</td>
<td>7.2%</td>
</tr>
<tr>
<td>16 kbps</td>
<td>43.1</td>
<td>33.8</td>
<td>36.6</td>
<td>8.3%</td>
</tr>
<tr>
<td>32 kbps</td>
<td>21.7</td>
<td>14.6</td>
<td>16.5</td>
<td>13.0%</td>
</tr>
<tr>
<td>64 kbps</td>
<td>11.0</td>
<td>5.8</td>
<td>7.1</td>
<td>30.0%</td>
</tr>
<tr>
<td>128 kbps</td>
<td>5.7</td>
<td>2.1</td>
<td>2.9</td>
<td>38.1%</td>
</tr>
</tbody>
</table>

### 2.3 (W)CDMA Downlink Capacity

In the CDMA downlink all the users connected to a certain base station share both the pool of orthogonal codes and the total base station output power. On top of the dedicated (i.e. “traffic”) channels, a number of common channels are also transmitted. Another fundamental difference in the downlink is the synchronization that is common to all users and channels of one cell (unlike the uplink where all users are non-synchronized). This enables the utilization of the cross-correlation properties of a special set of codes known as orthogonal variable spreading factor (OVSF) codes. These codes offer perfect cross-correlation (in an ideal) channel, but there is only a finite number of them available. In
reality, the orthogonality of the OVSF codes is affected by the multipath propagation, and according to the severity of the channel, a degree of intracell interference is experienced. Typically, a parameter called the “downlink orthogonality factor” \( \alpha \) is used to describe the amount of intracell interference.

![Figure 11. CDMA downlink interference scenario.](image)

Together with the intracell interference \( (I_{hc}) \), the total downlink interference consists of the intercell interference \( (I_{ic}) \) and the thermal noise power \( (N) \), see Figure 11. What is special about the downlink is that both the received carrier and the interference power depend on the location of the mobile. Furthermore, the path loss, slow and fast fading affecting the carrier and interference are partly correlated due to the fact that both the carrier and the intracell interference power are transmitted from the same location. This correlation has a noticeable effect on the received \( C/I \) (as well as the required \( \text{Rx } Eb/N0 \)) close to the serving base station, where the major part of the total interference is in fact intracell interference.

Assuming that the downlink is not limited by the number of orthogonal codes, the only limitation is thus the maximum total base station output power, \( P_{BS_{max}} \). Hence, the downlink capacity can be obtained by studying the required total base station output power as a function of the number of users [12][13].

In general, the total base station output power consists of the power allocated for the dedicated channels, taking the soft handover overhead into account, and the power allocated for the common channels \( (P_{CCH}) \). Thus,

\[
P_{int,m} = \sum_{i=1}^{K} v_i P_{i,m} + P_{CCH,m}
\]  \hspace{1cm} (2.30)
where $\nu_i$ is the activity factor and $P_{i,m}$ is the power allocated for the $i$th dedicated channel. Furthermore, the average number of radio links connected to a base station can be calculated as

$$K = M \sum_{x=1}^{AS} x \varepsilon_x$$  \hfill (2.31)

In equation (2.31), it is assumed that the average number of users per cell is $M$, maximum size of the active set is $AS$, and $\varepsilon_x$ is the probability that the active set has $x$ links.

The required transmit power towards a certain user can be solved from the downlink SIR equation

$$\frac{E_b}{N_0} = \frac{W}{R_i} \left( \alpha_{i,m} + F_{i,m} \right) \frac{P_{i,m}}{P_{tot,m}} + N L_{i,m} = \frac{W}{R_i} \left( \alpha_{i,m} + F_{i,m} \right) \frac{P_{i,m}}{P_{tot,m}} + N k_{i,m} L_c$$

which gives

$$P_{i,m} = \frac{E_b}{N_0} \left| \frac{R_i}{W} \right| \left( \alpha_{i,m} + F_{i,m} \right) \frac{P_{tot,m}}{P_{tot,m}} + N k_{i,m} L_c$$ \hfill (2.33)

where $W$ is the chip rate, $R_i$ is the bit rate for user $i$, $P_{i,m}$ is the downlink power allocated for user $i$, $\alpha_{i,m}$ is the downlink orthogonality factor for user $i$, $F_{i,m}$ is the inter-to-intracell interference ratio for the location of user $i$, $P_{tot,m}$ is the total output power for the serving base station $m$, $L_{i,m}$ is the path loss between user $i$ and the serving base station $m$, $L_c$ is the path loss between the serving base station receiver and the cell border, $k_{i,m}$ is the ratio between $L_{i,m}$ and $L_c$, $N$ is the thermal noise power, $\rho_i$ is the required carrier-to-interference ratio (CIR) for user $i$.

Furthermore, the inter-to-intracell interference ratio is defined as

$$F_{i,m} = \frac{L_{i,m}}{L_{b,m}} \sum_{b=1}^{B} \frac{P_{tot,b}}{L_{b,m}}$$ \hfill (2.34)

Here, it should be noticed that the fast power control and the soft handover will have a similar impact on the downlink as for the uplink. The difference is that in case of the...
downlink the average transmit power increase depends both on the soft handover situation and the location of each user. Therefore, the $\rho$ in equation (2.23), which takes the impact of both the fast power control and the soft handover into account, has typically a different value for each user.

Assuming a typical Okumura-Hata type of propagation model, the path loss $L_c$ can be calculated as

$$
(L_c)_{dB} = A + B \cdot 10 \log(d_c) + L_{add} - G_{RBS} - G_{UE} + M_{sh}
$$

(2.35)

where $A$ is the attenuation constant,

$B$ is the attenuation factor,

$d_c$ is the cell range,

$L_{add}$ are the additional losses (e.g. feeder loss, body loss etc),

$G_{RBS}$ is the base station antenna gain,

$G_{UE}$ is the mobile station antenna gain,

$M_{sh}$ is the shadow fading margin for the required coverage probability level, including the possible soft handover gain.

The required total average power allocated for the common channels, $P_{CCH,m}$ depends also on the cell size, but also on the cell load. The dependency on the cell load is twofold: Firstly, the required peak powers for the common channels depend on the $P_{tot,m}$ in a similar way as shown in (2.33) for the dedicated channels. Secondly, the activity factor for some of the downlink common channels depends on the number of users due to the fact that the channels in question are used to carry information towards specific users.

Furthermore, one can assume that the ratio between the common channel peak powers is fixed. Therefore, it is enough to check the quality for only one of them, Common Pilot Channel (CPICH) in this case, and the required peak powers for the others can then be derived from the $P_{CPICH}$. The required $P_{CPICH}$ can be solved from the CPICH CIR equation for the cell coverage border as

$$
\gamma = \frac{P_{CPICH,m}}{(\alpha_c + F_c)P_{tot,m} + NL_c}
$$

$$
\Rightarrow P_{CPICH,m} = \gamma \cdot ((\alpha_c + F_c)P_{tot,m} + NL_c)
$$

(2.36)

where $\alpha_c$ is the downlink orthogonality factor at the cell coverage border,

$F_c$ is the inter-to-intracell interference ratio at the cell coverage border,

$\gamma$ is the required CIR for the CPICH.

In the simplest case, there is a linear dependency between the $P_{CCH,m}$ and the $P_{CPICH,m}$. Thus,
\[ P_{CCH,m} = (C_c + C_l M) P_{CPICH,m} \]
\[ = (C_c + C_l M) \cdot \gamma \cdot ((\alpha_c + F_c) P_{tot,m} + NL_c) \quad (2.37) \]

where \( C_c \) is the total average load-independent common channel power (normalized to the CPICH power),
\( C_l \) is the total average load-dependent common channel power (normalized to a reference load level and to the CPICH power).

Now, assuming a single service system, and following the approach presented in [13], the users can be divided into different subgroups based on the number of active links they have. Hence, the average total base station output power becomes
\[ P_{tot} = MP_{tot} \cdot \sum_{x=1}^{AS} x \epsilon_x v_x \rho_x (\alpha_x + F_x) + MNL_c \cdot \sum_{x=1}^{AS} x \epsilon_x v_x \rho_x k_x + P_{CCH} \quad (2.38) \]

where \( v_x \) is the average activity factor,
\( \rho_x \) is the average Rx CIR,
\( \alpha_x \) is the average downlink orthogonality factor,
\( F_x \) is the average inter-to-intracell interference ratio,
\( k_x \) is the average \( k_{i,m} \)-factor for user group \( x \).

Solving the above equation for \( P_{tot} \) gives
\[ P_{tot} = \frac{NL_c (M (\mu + C_l \gamma) + C_c \gamma)}{1 - C_c \gamma (\alpha_c + F_c) - M (\beta + C_l \gamma (\alpha_c + F_c))} \quad (2.39) \]

where
\[ \mu = \sum_{x=1}^{AS} x \epsilon_x v_x \rho_x k_x \quad (2.40) \]
\[ \beta = \sum_{x=1}^{AS} x \epsilon_x v_x \rho_x (\alpha_x + F_x) \quad (2.41) \]

Now, the downlink pole capacity, \( M_{pole} \), can be solved by assuming
\[ P_{tot} \to \infty \]
which gives
\[ M_{pole} = \frac{1 - C_c \gamma (\alpha_c + F_c)}{\beta + C_l \gamma (\alpha_c + F_c)} \quad (2.42) \]

Thus, the equation for the \( P_{tot} \) can be re-written as
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\[ P_{tot} = \frac{NL_c (\eta M_{pole} (\mu + C_c \gamma) + C_c \gamma)}{(1 - C_c \gamma (\alpha_c + F_c))(1 - \eta)} \]  \hspace{1cm} (2.43)

where

\[ \eta = \frac{M}{M_{pole}} \]  \hspace{1cm} (2.44)

In Figure 12 the \( P_{tot} \) as a function of the relative downlink load \( \eta \) is drawn for different maximum path loss \( L_c \) values. There, the parameter values listed in Table 4 are assumed, resulting in a \( M_{pole} \) equal to 42.0 users.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho_{dB} )</td>
<td>-18 dB</td>
</tr>
<tr>
<td>( \nu )</td>
<td>0.67</td>
</tr>
<tr>
<td>( \mu )</td>
<td>0.29* ( \nu ) ( P_{lin} )</td>
</tr>
<tr>
<td>( \beta )</td>
<td>1.6* ( \nu ) ( P_{lin} )</td>
</tr>
<tr>
<td>( \alpha_c )</td>
<td>0.64</td>
</tr>
<tr>
<td>( F_c )</td>
<td>2.1</td>
</tr>
<tr>
<td>( C_c )</td>
<td>1.8</td>
</tr>
<tr>
<td>( C_i )</td>
<td>( 1.4/25 = 0.056 )</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>-16 dB</td>
</tr>
<tr>
<td>( P_{BSmax} )</td>
<td>20 W</td>
</tr>
<tr>
<td>( \Omega )</td>
<td>0.3* ( P_{BSmax} )</td>
</tr>
<tr>
<td>( N )</td>
<td>-100 dBm</td>
</tr>
</tbody>
</table>

Table 4. Downlink assumptions.

For stability reasons the relative downlink load should not be too high, e.g. above 0.8. On top of that, in reality, the \( P_{tot} \) will be limited to a certain maximum value, \( P_{BSmax} \). Therefore, in order to obtain a reasonably low base station overload probability in larger cells, a special margin, “headroom” \( \Omega \), should be left between \( P_{BSmax} \) and the maximum allowable average base station output power \( P_{tot} \). Taking this into account, the maximum downlink capacity, \( M_{max} \) becomes

\[ M_{max} = M_{pole} \cdot \min \left( \eta_{max}, \frac{(P_{BSmax} - \Omega)(1 - C_c \gamma (\alpha_c + F_c)) - NL_c C_c \gamma}{(P_{BSmax} - \Omega)(1 - C_c \gamma (\alpha_c + F_c)) + M_{pole} NL_c (\mu + C_c \gamma)} \right) \]  \hspace{1cm} (2.45)
The size of the required headroom depends among other things on the service and the cell load level, as shown in [12]. However, taking into account the impact of the downlink admission and congestion control resulting in user blocking and dropping, respectively, the size of the headroom can be somewhat decreased.
are both 0.4 dB larger than the corresponding average values. As a result, the corresponding $P_{tot,conf}$ curves together with the original $P_{tot}$ curves are shown in Figure 13.

Now, the maximum downlink capacity is the number of users, when the $P_{tot,conf}$ becomes equal to $P_{BS_{max}}$. Thus,

\[
M_{max} = \min\left( \eta_{max} M_{pole}, \frac{1 - C_{c} \gamma (\alpha_{c} + F_{c})}{\left( \beta_{conf} + C_{i} \gamma (\alpha_{c} + F_{c}) \right) P_{BS_{max}} + NL_{c} \left( \mu_{conf} + C_{i} \gamma \right)} \right)
\]

Finally, in Figure 14 the maximum downlink capacity $M_{max}$ as a function of the $L_{c}$ is presented. There, it is assumed that the $P_{BS_{max}}$ is 20 W. Furthermore, the maximum allowed value for the $\eta$ is assumed to be equal to 0.8.

**Figure 14. Maximum number of users per cell as a function of the cell size.**

### 3 SUMMARY

In this paper the CDMA uplink and downlink capacity is discussed, and simple semi-analytical expressions are derived. Furthermore, the impact of fast power control and soft handover on CDMA system capacity is discussed also.

### 4 REFERENCES


