Next we choose the link with the least acceptable path loss to calculate the cell radius. In this case the coverage will be limited by uplink. Hand-held units inside a building experience an additional path loss that is dependent on building type, building material, and placement of the user within the building. Changing antenna height, gains, or use of antenna diversity will also affect coverage under noise-limited conditions.

We use uplink path loss and Hata model to calculate cell radius as:

$$L_p = 133.2 + 33.8 \log R; \text{ where } R \text{ is the cell radius in kilometers.}$$

$$\therefore R = 10^{(135.8-133.2)/33.8} = 1.2\,\text{km}$$

17.4.2 Pole Capacity of a CDMA Cell

To determine the pole capacity of a CDMA cell, we consider a user with the received signal strength of S at the base station and account for interference from $(M-1)$ users in its own cell, I_{own} and M users in other cells, I_{other} along with thermal power N_{th}. We assume the same signal strength at the base station from other users.

$$I_{own} = (M-1)Sv_f$$

where:

v_f = channel activity
$N_{th} = N_0 B_w$

Total interference including thermal noise power:

$$I_t = I_{own} + I_{other} + N_{th} = [(1+\beta)M - 1]v_f S + N_0 B_w$$
$$= \left[\frac{M}{\eta} - 1\right] S v_f + N_0 B_w \qquad (17.1)$$

where:

$\eta = \dfrac{1}{1+\beta}$ = Total same-cell power/(Total same-cell power + Other cells power)

$$\text{Cell loading} = \rho = \frac{M}{M_{max}} \approx \frac{I_{own} + I_{other}}{I_{own} + I_{other} + N_{th}} \qquad (17.2)$$

$$\frac{E_b}{I_t} = G_p \cdot \frac{S}{N_0 B_w + (M-1)v_f(S/\eta_c)(1+\beta)} \qquad (17.3)$$

Solving Equation 17.3 for M, we get

$$M = 1 + G_p \left[\frac{\eta_c}{(E_b/I_t)\upsilon_f(1+\beta)} \right] - \frac{N_0 B_w}{S\upsilon_f(1+\beta)} \tag{17.4}$$

and solving Equation 17.3 for S, we get

$$S = \frac{(E_b/I_t)N_0}{\dfrac{1}{R} - \dfrac{(M-1)\upsilon_f(1+\beta)(E_b/I_t)}{B_w \eta_c}} \tag{17.5}$$

$$\therefore M_{\max} \approx \frac{G_p}{d} \cdot \frac{1}{(1+\beta)} \cdot \frac{\eta_c}{\upsilon f}; \quad = \frac{R_c}{R_i} \cdot \frac{1}{1+\beta} \cdot \frac{1}{v_i} \cdot \frac{1}{(E_b/N_t)} \tag{17.6}$$

where:

η_c = power control efficiency (often 80% to 85%)
β = interference factor due to other cells
$d = (E_b/I_t)_{\text{reqd}}$
G_p = processing gain
N_0 = noise density
R = information rate

Equation 17.6 is known as the *pole capacity* of a cell. We rewrite Equation 17.5 as

$$\frac{S\eta_c}{N_0 B_w} = \frac{1}{M_{\max}\, \upsilon_f (1+\beta)(1-\rho)} \tag{17.7}$$

Note when ρ tends to 1, $S\eta_c$ tends to infinity because interference tends to infinity.

17.4.3 Uplink Radio Link Budget for a CDMA System

We consider an ith mobile in a given cell. The required $(E_b/I_t)_i = d_i$ for the ith mobile is given as:

$$\frac{R_c}{R_i} \cdot \frac{S_i}{I_{\text{own}} - S_i + I_{\text{other}} + N_{\text{th}}} = \frac{R_c}{R_i} \cdot \left(\frac{S_i}{I_{\text{own}} - S_i + \beta I_{\text{own}} + N_{\text{th}}} \right) \ge d_i,\ i = 1, 2, \ldots M \tag{17.8}$$

where:

R_c = chip rate
R_i = information rate for ith mobile
I_{own} = interference for ith mobile from its own cell

$I_{other} = \beta I_{own}$ = interference from other cells
N_{th} = thermal noise power for ith mobile = $N_f k T_\phi R_c$
$d_i = (E_b/N_t)_{reqd}$ for ith mobile
N_f = receiver noise figure for ith mobile
k = Boltzmann constant
T_ϕ = Absolute temperature

Solving the inequalities in Equation 17.8 as equalities means solving for the minimum required power (sensitivity) S_i as

$$S_i = \left(\frac{1}{1 + \frac{R_c}{R_i d_i}}\right) \cdot (1 + \beta) I_{own} + \frac{1}{1 + \frac{R_c}{R_i d_i}} N_{th} \quad i = 1, 2, \ldots M \tag{17.9}$$

If Equation 17.9 is summed over the mobile stations, M, connected to a particular base station, then

$$\sum_{i=1}^{M} S_i = \left[\sum_{i=1}^{M}\left(\frac{1}{1 + \frac{R_c}{R_i d_i}}\right) \cdot (1 + \beta)\right] \cdot \sum_{i=1}^{M} S_i + \sum_{i=1}^{M} \frac{1}{1 + \frac{R_c}{R_i d_i}} \cdot N_{th} \tag{17.10}$$

$$\therefore \sum_{i=1}^{M} S_i (1 + \beta) = \frac{N_{th}\left[\sum_{i=1}^{M} \frac{1}{1 + \frac{R_c}{R_i d_i}} \cdot (1 + \beta)\right]}{1 - \left[\sum_{i=1}^{M} \frac{(1 + \beta)}{1 + \frac{(1 + \beta)}{1 + \frac{R_c}{R_i d_i}}}\right]} \tag{17.11}$$

we define the uplink loading as:

$$\eta_{UL} = \left[\sum_{i=1}^{M} \frac{1}{1 + \frac{R_c}{R_i d_i}}\right] \cdot (1 + \beta) \tag{17.12}$$

where:

η_{UL} = uplink loading

Next, we modify Equation 17.12 to include the effect of sectorization (sectorization gain, λ, number of sector, N_s) and channel activity factor υ_i then

$$\eta_{UL} = \left[\sum_{i=1}^{M} \frac{1}{1 + \frac{R_c}{R_i d_i} \cdot \frac{1}{\upsilon_i}}\right] \cdot \left(1 + \beta \cdot \frac{N_s}{\lambda}\right) \tag{17.13}$$

Imp

Example 17.5

Calculate the uplink cell load-factor and number of voice users for a WCDMA system using the following data. What is the pole capacity of the cell?

- Information rate (R_i): 12.2 kbps
- Chip rate (R_c): 3.84 Mcps
- Required E_b/N_t: 4 dB
- Required interference margin: 3 dB
- Interference factor due to other cells: 0.5
- Channel activity factor: 0.65 $= V_i$

Solution

From Equation 17.13:

$$\text{Load-factor} = (1+\beta)\cdot\sum_{i=1}^{M}\frac{1}{1+\dfrac{R_c}{R_i}\cdot\dfrac{1}{(E_b/N_t)_{\text{reqd}}}\cdot\dfrac{1}{\upsilon_i}}$$

0.00774.

$$\text{Load-factor per voice user} = (1+0.5)\cdot\frac{1}{1+\dfrac{3840}{12.2}\cdot\dfrac{1}{2.512}\cdot\dfrac{1}{0.65}} = 000774$$

$$\text{Required interference margin} = 3\,\text{dB} = 2 = \frac{1}{1-\rho}$$

$$\text{Cell loading} = \rho = 0.5$$

$$\text{Number of voice users} = \frac{0.5}{0.00774} \approx 64 \text{ per cell}$$

Using Equation 17.6 and assuming $\eta_c = 1$ (for this case), we get the pole capacity of the cell as

$$M_{\max} = \frac{3.84\times10^6}{12.2\times10^3}\cdot\frac{1}{0.65}\cdot\frac{1}{(1+0.5)}\cdot\frac{1}{2.52} = 128$$

Imp.

Example 17.6

Calculate the uplink throughput for data service only for a WCDMA cell using the following information:

- Required E_b/N_t: 1 dB
- Required interference margin: 3 dB (cell loading = 0.5)

- Interference factor due to other cells: 0.5 $= \beta$
- Channel activity factor: 1.0

Solution

$$\text{Load factor} = M(1+\beta)\cdot\frac{1}{1+\frac{R_c}{R_i}\cdot\frac{1}{(E_b/N_t)_{\text{reqd}}}\cdot\frac{1}{\upsilon_i}} \approx M(1+\beta)\cdot\frac{1}{\frac{R_c}{R_i}\cdot\frac{1}{(E_b/N_t)_{\text{reqd}}}\cdot\frac{1}{\upsilon_i}}$$

$$\text{Throughput} = R_i \times M = \frac{\text{cell loading} \times R_c}{(E_b/N_t)_{\text{reqd}}\cdot(1+\beta)} = \frac{0.5\times 3840}{1.259\times 1.5} = 1016\,\text{kbps}$$

17.4.4 Downlink Radio Link Budget for a CDMA System

Downlink dimensioning uses the same method as uplink [7]. For a selected range the total base station transmit power must be estimated. In this estimation the soft handoff connections must be included. If the power exceeds that estimated, either the cell range should be limited or the number of users in the cell should be reduced.

$$\eta_{DL} = \sum_{i=1}^{I}\left[\frac{R_i d_i \upsilon_i}{R_c}\left\{\xi_i + \sum_{n=1,\,n\neq m}^{N}\frac{L_{pmi}}{L_{pni}}\right\}\right] \tag{17.14}$$

where:

L_{pmi} = link loss from serving BS m to ith mobile station (MS)
L_{pni} = link loss from the other BS n to ith MS
d_i = transmit (E_b/N_t) requirement for ith MS including the soft handoff combining gain and average power rise caused by fast power control
N = number of base stations
I = number of connections in a sector
ξ_i = orthogonality factor $(0 \le \xi_i \le 1)$; $\xi_i = 1$, fully orthogonal
$i_{DL} = \sum_{n=1,\,n\neq m}^{N}\frac{L_{pmi}}{L_{pni}}$ defines the average other-to-own cell interference in downlink

The total base station transmit power estimation must take into account multiple communication links with average distance $(\bar{L}_{pmi})$ from the serving BS. In the radio link budget calculations in the uplink, the limiting factor is MS transmit power; in the downlink the limiting factor is total base station transmit power. While balancing the uplink and downlink service areas both links must be considered.

The interference degradation margin to be taken into account in the link budget due to certain loading ρ (in either uplink or downlink) is

$$L = 10\log(1 - \rho) \tag{17.15}$$

Some margin is required in MS transmission power to maintain adequate closed-loop fast power control in unfavorable propagation conditions such as near the cell edge. This applies especially to pedestrian users, where the E_b/N_t to be maintained is more sensitive to closed-loop power control.

Imp

Example 17.7

Calculate the downlink cell load-factor and number of voice users per cell for a WCDMA system using the following data.

- Information rate (R_i): 12.2 kbps
- Chip rate (R_c): 3.84 Mcps
- Required E_b/N_t: 4 dB
- Average interference factor due to other cells: 0.5
- Orthogonality factor (ξ): 0.6
- Interference margin: 3 dB

Solution

$$\eta_{DL} = (\xi + i_{DL}) \cdot \sum_{i=1}^{I} \frac{1}{\frac{R_c}{R_i} \cdot \frac{1}{(E_b/N_t)_{reqd}} \cdot \frac{1}{v_i}}$$

$$\text{Load-factor per voice user} = (0.6 + 0.5) \cdot \frac{1}{\frac{3840}{12.2} \cdot \frac{1}{2.512} \cdot \frac{1}{0.65}} = 0.0057$$

$$\text{Interference margin} = 3\,\text{dB} = 2 = \frac{1}{1-\rho};\ \rho = 0.5$$

$$\text{Number of voice users} = \frac{0.5}{0.0057} \approx 87 \text{ per cell}$$

Example 17.8

Determine the minimum signal power required for the acceptable quality of voice at the base station receiver of an IS-95 CDMA system. What is the maximum allowable path loss? Use the following data and refer to Figure 17.4.

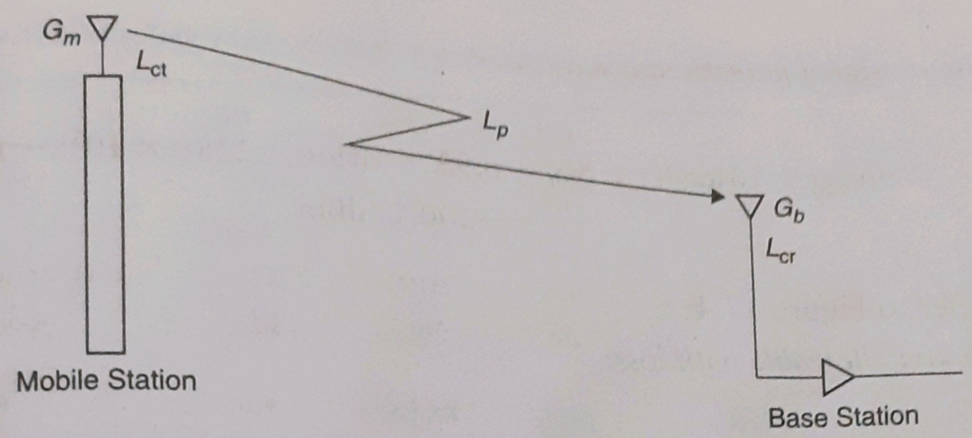

Figure 17.4 Uplink transmission from MS to BS.

- Noise density (N_0) = −174 dBm/Hz
- Channel bandwidth (B_c) = 1.25 MHz
- Chip rate (R_c) = 1.2288 Mcps
- Receiver noise figure (N_f) = 6 dB
- Effective radiated power of the mobile = 0.5 Watt (27 dBm)
- Transmitter cable and connector loss (L_{ct}) = 0.5 dB
- Body loss (L_{body}) = 1.5 dB
- Receiver cable and connector loss (L_{cr}) = 2 dB
- Interference margin (m_{inf}) = 0 dB
- Fast fading margin (m_{fading}) = 2 dB
- Penetration losses (L_{pent}) = 8 dB
- Transmitter antenna gain (G_m) = 0 dBi
- Receiver antenna gain (G_b) = 12 dBi
- Fade margin (f_m) = 8 dB
- Required E_b/N_t = 7 dB

Solution

Base station noise floor:

$$N_{th} = N_0 + N_f = -174 + 6 = -168\ \text{dBm/Hz}$$

Required S/N_t:

$$(S/N_t)_{reqd} = (E_b/N_t)_{reqd} + 10\log(R_c/B_c) = 7 + (10)\log\left(\frac{1.2288}{1.25}\right) = 6.93\ \text{dB}$$

Minimum signal power required:

$$S_{min} = (S/N_t)_{reqd} + 10\log R_c + N_{th} = 6.93 + 10\log(1.2288 \times 10^6) - 168$$
$$= -100.17\,\text{dBm}$$

We refer to Figure 17.4:

Maximum allowable path loss:

$$L_{pmax} = (P_m - S_{min}) + (G_b + G_m) - (L_{body} + L_{ct} + L_{cr} + f_m + L_{pent}) - m_{int} - m_{fading}$$
$$= 27 - (-100.17) + (12 + 0) - (1.5 + 0.5 + 2.0 + 8 + 8) - 2 = 117.17\,\text{dB}$$

Example 17.9

Develop a radio link budget for uplink and downlink of a WCDMA system using the following data (including Table 17.1):

- Chip rate: 3.84 Mcps
- Data rate: 16 kbps
- UL loading: 50%
- DL loading: 90%
- Required E_b/N_t uplink: 4 dB
- Required E_b/N_t downlink: 6 dB
- Mobile antenna gain: 0 dBi
- Base station antenna gain: 18 dBi

Solution

The Okumura-Hata model for an urban macro-cell with a base station antenna height of 25 m, a mobile antenna height of 1.5 m, and a carrier frequency of 1950 MHz gives

$$L_p = 138.5 + 35.7\log R$$

where:

L_p = allowable path losses (dB)
R = hexagonal cell radius (km)

What is the cell radius based on the calculated allowable path loss?

$$139.65 = 138.5 + 35.7 \log R$$

$$\therefore R = 1.077\,\text{km}$$

Area covered by hexagonal cell $= 2.6 \times R^2 = 3.02 \sim 3.0\,\text{km}^2$
Number of BTSs required to cover an area of $2400\,\text{km}^2 = 800$

Example 17.10

During a busy hour an average user downloads 10 megabits with 384 kbps, 2 megabits with 144 kbps, and 1 megabit with 64 kbps. Data has to be retransmitted 1.2 times the average because of network conditions. Calculate the number of users that can be supported on the downlink of the WCDMA network. Use the following data:

- Spreading rate (R_c): 3.84 Mcps
- Noise rise: 3 dB
- Orthogonality factor (α): 0.8
- Interference from other cells (β): 0.55
- $(E_b/N_0)_{\text{reqd}}$: 4 dB
- Sector efficiency (λ): 0.85
- Power control efficiency (η_c): 0.80

Solution

Service rate	*Average data rate*
• $1.2 \times 10 \times 10^3/3600$	3.33 kbps
• $1.2 \times 2 \times 10^3/3600$	0.67 kbps
• $1.2 \times 1 \times 10^3/3600$	0.33 kbps
Total:	4.33 kbps

$$\text{Noise rise} = 3\,\text{dB} = 2 = \frac{1}{1-\rho}$$

$$\rho = 0.5$$

$$\text{DL capacity} = \frac{R_c}{(E_b/N_0)_{\text{reqd}}} \cdot \frac{\eta_c}{(\alpha+\beta)} \cdot \frac{\lambda}{\upsilon_f} = \frac{3.84 \times 10^3}{2.5} \cdot \frac{0.80}{1.35} \cdot \frac{0.85}{1} = 774\,\text{kbps}$$

$$\text{Allowable DL capacity} = \rho \times \text{DL capacity} = 0.5 \times 774 = 387\,\text{kbps}$$

$$\text{Number of users} = \frac{387}{4.33} \approx 89$$

In this case the latency of user classes will be the same. For the general case of N classes and latency ratio $L_{max}/L_{min} = \rho_L$, the maximum achievable throughput C is given as:

$$C = \frac{\sum_{i=1}^{K} P_i + \sum_{i=K+1}^{N} P_i \rho_L}{\sum_{i=1}^{K} \frac{P_i}{R_i} + \sum_{i=K+1}^{N} \left(\frac{P_i}{R_i}\right) \rho_L} \quad (17.19)$$

where:

$R_1 < R_2 < R_3 \cdots < R_N$; K is such that $R_i \le C$ for all $i \le K$, while $R_i > C$ for all $i > K$.

In this case each user's latency is either L_{max} (for those $R_i < C$) or L_{min} (for those $R_i > C$).

In the equal access situation we assign a number of slots to each user based on the requested data rate. The average throughput will be:

$$R_{av} = \frac{\sum_{i=1}^{N} S_i P_i R_i}{\sum_{i=1}^{N} S_i P_i} \quad (17.20)$$

where:

S_i = number of slots assigned to the R_i user

Imp.

Example 17.11

Consider a data system in which $P_1 = 1/2$, $P_2 = 1/3$, and $P_3 = 1/6$. The data rates are $R_1 = 16$ kbps, $R_2 = 64$ kbps, and $R_3 = 1024$ kbps, respectively. The assigned slots are $S_1 = 16$, $S_2 = 8$ and $S_3 = 2$. What is the average throughput? Compare it with the equal latency and $\rho_L = 4$ cases.

Solution

Using Equation 17.20:

$$R_{av} = \frac{16 \times 16 \times \frac{1}{2} + 8 \times 64 \times \frac{1}{3} + 2 \times 1024 \times \frac{1}{6}}{16 \times \frac{1}{2} + 8 \times \frac{1}{3} + 2 \times \frac{1}{6}} = 58.2\,\text{kbps}$$

For equal latency, using Equation 17.18:

$$R_{av} = \frac{1}{\frac{1}{2} \times \frac{1}{16} + \frac{1}{3} \times \frac{1}{64} + \frac{1}{6} \times \frac{1}{1024}} = 27.3\,\text{kbps}$$

For $\rho_L = 4$, using Equation 17.19:

$$C = \frac{\frac{1}{2} + \frac{1}{3} + 4 \times \frac{1}{6}}{\frac{1}{2 \times 16} + \frac{1}{3 \times 64} + \frac{1}{6 \times 1024}} = 40.96\,\text{kbps}$$

It can be observed that equal access provides the highest average throughput.

17.5.2 Details of cdma2000 1X EV-DO

Figure 17.5 shows an overview of downlink channels of the cdma2000 1X EV-DO system. The pilot, traffic, medium access, and control channels are time division multiplex (TDM) channels. The medium access channel consists of two code division multiplex (CDM) channels, and reverse activity and reverse power control channels. The control channel is used for system acquisition, system parameters broadcast, and service negotiations during call setup. The pilot channel is used to provide coherent reception, soft handoff, channel estimation, and long-range prediction and rate selection. The reverse activity channel is used for uplink overload and rate control to indicate the uplink interference loading of the sector. The reverse power control channel is used for fast power control of the existing uplink connections. The traffic channel is used to transmit data to the multiple users in a TDM fashion. The time slots have a duration of 1.67 ms (see Figure 16.23) and could be assigned to any user as determined by the scheduling algorithm. The data on the traffic channel can be transmitted at 38.4, 76.8, 153.6, 307.2, 614.4, 921.6, 1228.8, 1843.2, and 2457.6 kbps. The higher data rates are obtained using a combination of higher order modulation (QPSK, 8-PSK, 16-QAM), forward

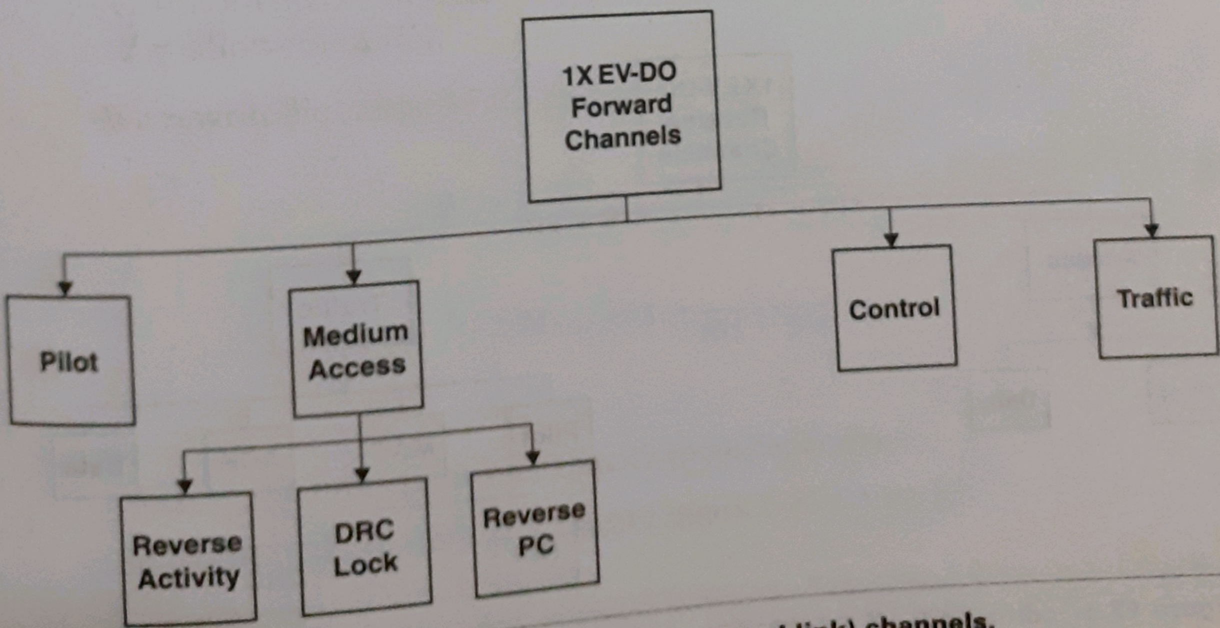

Figure 17.5 cdma2000 1X EV-DO downlink (forward link) channels.

Table 17.2 DL traffic channel gains relative to pilot [3].

Traffic channel rate (kbps)	Traffic channel gain (dB) relative to pilot
9.6	3.75
19.2	6.75
38.4	9.75
76.8	13.25
153.6	18.5

The sector loading can be expressed as a fraction of the pole capacity M_{max}. This is typically 70% of the pole capacity.

The dependency of the traffic channel gain G_T on the data rate is given in Table 17.2 and is based on the recommendation in [1]. The DRC channel gain is a function of the number of slots in which the same value of DRC is repeated. A DRC length of 2 slots provides an acceptable trade-off between the up- and downlink performance [5]. The recommended value of the DRC channel gain, G_D, is -1.5 dB.

Imp

Example 17.12

Find the allowable throughput of the reverse link in cdma2000 1X EV-DO if the average rate on the reverse traffic channel is 9.6 kbps. Use the following data:

- Allowable E_c/N_t: -23 dB
- DRC gain with respect to pilot: -1.5 dB
- Traffic channel gain with respect to pilot: 3.75 (see Table 17.2)
- Interference factor due to other cells (β): 0.85

Solution

$$M_{max} = \frac{1}{(1 + 10^{-0.15} + 10^{0.375})} \cdot \frac{1}{10^{-2.3} \times 1.85} = 26.4$$

$$M_{allowable} = 0.7 \times 26.4 \approx 18$$

$$\text{Reverse link throughput} = 173\,\text{kbps}$$

17.6 High-Speed Downlink Packet Access

We discussed high-speed downlink packet access (HSDPA) in Chapter 15. In this section we present the link budget and throughput calculations of the high-speed downlink shared channel (HS-DSCH) [6,10].