Estimation of Capacity and Required Transmission Power of WCDMA Downlink Based on a Downlink Pole Equation

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Abstract - A simple method is derived for estimating the downlink capacity and required base station transmission power in a WCDMA system. This is based on a downlink pole equation which is mostly similar with the well known CDMA uplink pole equation. It is shown that the total downlink transmission power is composed of two terms. The first term is equal to what would be needed in the absence of interference and the second one shows the increase due to multiple access interference, which is inversely proportional to $1-\eta_{DL}$ where η_{DL} is called the downlink loading. The method can be used in radio network dimensioning where extensive simulations can not be run. Usage of the method is demonstrated by some examples.

I. Introduction

In WCMDA radio network dimensioning the uplink power budget is based on the well known link quality equation, see e.g. [1]:

$$p_i = \frac{P_N \frac{\rho_i R_i}{W} L_i}{1-\eta_{UL}}, \qquad (1)$$

with

$$\eta_{UL} = \sum_i \frac{\rho_i R_i v_i}{W}\left(1+f_{UL}\right). \qquad (2)$$

In here the required transmission power p_i of user equipment (UE) i is determined by the noise power P_N, E_b/N_0 requirement ρ_i, bit rate R_i, path loss L_i, chip rate W and loading η_{UL}. The loading is calculated by summing the loading factors of individual connections over the cell according to Equation (2). In Equation (2) v_i is the channel activity factor and f_{UL} is the other-to-own-cell received interference ratio at basestation (BS). The pole capacity is achieved when η_{UL} approaches one but in practice the maximum allowed loading must be kept clearly below one to ensure stability of network.

By simple manipulation of Equation (1) the maximum allowed path loss can be calculated if the maximum transmission power of UE is known. This is the basis for the uplink link budget in WCDMA radio network dimensioning.

In downlink the situation is different 1) since usually multiple or all connections share one BS power amplifier, 2) since the interference from the serving cell is received through the same propagation channel as the signal and 3) since different UE:s experience different interference from neighbouring cells depending on the location. Still, it can be expected that in downlink there is similar type of non-linearity in the required transmission power as a function of loading, as in the uplink.

The target of this paper is to ease WCDMA downlink dimensioning by providing simple formulas to estimate downlink loading and the required BS transmission power. It will be seen in Chapter II that this can be done in analogy with uplink by using a *downlink pole equation.* The greatest difference when compared to uplink is the inclusion of an orthogonality factor due to mutually orthogonal spreading codes within a cell. The usage of the pole equation is demonstrated by examples in Chapter III.

Similar type of analysis has been presented in [2, Ch. 11] in terms of IS-95 standard. The reference WCDMA system studied here is based on the 3GPP WCDMA/FDD standard.

II. Downlink pole equation

The derivation of the downlink pole equation starts from the assumption that due to the fast power control the UE:s are able to obtain exactly the minimum average E_b/N_0 denoted by ρ_i, required for the service. It is also assumed that the total transmit power of different base stations is equal. This assumption is approximately valid for example if there is a regular grid of BS, if the traffic distribution is uniform and if the propagation conditions do not change over the studied area. The link quality equations for the downlink connections, in a cell m, can be written as

$$\frac{W p_i / L_{m,i}}{R_i\left((1-\alpha_i)P / L_{m,i} + P\sum_{n=1,n\neq m}^{N} 1/L_{n,i} + P_N\right)} = \rho_i, \qquad i=1,\dots,I. \qquad (3)$$

In Equation (3) p_i is the required transmit power at BS m for the connection i, $i = 1,\dots,I$, where I is the number of radio link (RL) connections in the cell. P_N is the (thermal) noise power, R_i is the bit rate, W is the chip rate, P is the required total transmit power of the BS, $L_{m,i}$ is the path loss from the serving BS m to UE i, $L_{n,i}$ is the path loss from another BS n, to UE i, ρ_i is the E_b/N_o requirement for the UE i, including the SHO combining gain and the average power raise caused by fast power control ([3], [4]), N is the number of relevant neighbouring base stations and v_i is the effective channel activity for the UE i (appears only in later equations).

The greatest difference in here when compared to uplink is the inclusion of α_i, the orthogonality factor, which depends on multipath propagation conditions ($\alpha = 1$: fully orthogonal in case of a single propagation path).

Solving Equations (3) for p_i gives

$$p_i = \frac{\rho_i R_i}{W}\left((1-\alpha_i)P + P \sum_{n=1,n\neq m}^{N} \frac{L_{m,i}}{L_{n,i}} + P_N L_{m,i} \right), \quad i = 1,\ldots,I. \tag{4}$$

The Equations (4) are multiplied by channel activity factors, v_i, and summed up over RL connections of the cell. This gives the following equality for the total downlink transmission power of the BS:

$$P = P\sum_{i=1}^{I}\left[\frac{\rho_i R_i v_i}{W}\left((1-\alpha_i) + \sum_{n=1,n\neq m}^{N} \frac{L_{m,i}}{L_{n,i}} \right)\right] + P_N \sum_{i=1}^{I} \frac{\rho_i R_i v_i}{W} L_{m,i} \tag{5}$$

Solving (5) for P gives

$$P = \frac{P_N \sum_{i=1}^{I} \frac{\rho_i R_i v_i}{W} L_{m,i}}{1 - \sum_{i=1}^{I}\left[\frac{\rho_i R_i v_i}{W}\left((1-\alpha_i) + \sum_{n=1,n\neq m}^{N} \frac{L_{m,i}}{L_{n,i}} \right)\right]}. \tag{6}$$

Thus it is convenient to define downlink loading, η_{DL}, as

$$\eta_{DL} = \sum_{i=1}^{I}\left[\frac{\rho_i R_i v_i}{W}\left((1-\alpha_i) + f_{DL,i} \right)\right], \tag{7}$$

where

$$f_{DL,i} = \sum_{n=1,n\neq m}^{N} \frac{L_{m,i}}{L_{n,i}} \tag{8}$$

Now the Equation (6) can be interpreted as: *the total power in downlink is equal to the transmission power which would be needed in the absence of interference + "noise rise" due to multiple access interference, which is in decibels* $NR_{DL} = -10 \cdot \log(1-\eta_{DL})$. Notice that under the assumption of equal total BS transmission powers the factor $f_{DL,i}$ defined in Equation (8) is equal to other-to-own-cell received power ratio for the connection i, at the position of the corresponding UE. The other-to-own-cell interference ratio in downlink can be defined as the average: $f_{DL} \triangleq \frac{1}{I}\sum_{i=1}^{I} f_{DL,i}$.

When η_{DL} approaches 1 the downlink capacity approaches to its maximum, pole capacity, where the required transmit power approaches to infinity.

Inserting P from Equation (6) to Equation (4) one can estimate the required power for an individual connection. That is,

$$p_i = X_i P + Y_i P_N, \tag{9}$$

where $X_i = \frac{\rho_i R_i}{W}(1-\alpha_i + \sum_{n=1,n\neq m}^{N} \frac{L_{m,i}}{L_{n,i}})$ and $Y_i = \frac{\rho_i R_i}{W} L_{m.i}$.

One important special case is the one with all connections using the same service with the same bit rate and quality requirement. In this case Equation (6) becomes

$$P = \frac{P_N \frac{\rho R v}{W} IL}{1 - \frac{\rho R v}{W} I\left[(1-\alpha) + f_{DL}\right]}, \tag{10}$$

where $\alpha \triangleq \frac{1}{I}\sum_{i=1}^{I}\alpha_i$ and $L \triangleq \frac{1}{I}\sum_{i=1}^{I} L_{m,i}$.

In practical radio network dimensioning it is not possible to use the parameters of each individual connection, but merely distributions. For this purpose the terms of Equation (6) can be grouped according to different user profiles, e.g. separating different services, mobility, propagation, SHO conditions etc., i.e.

$$P = \frac{P_N \frac{\rho^{(1)} R^{(1)} v^{(1)}}{W} I^{(1)} L^{(1)}}{1 - \sum_{j=1}^{N_g} \frac{\rho^{(j)} R^{(j)} v^{(j)}}{W} I^{(j)}\left(1-\alpha^{(j)} + f_{DL}^{(j)}\right)} + \ldots$$

$$\ldots + \frac{P_N \frac{\rho^{(N_g)} R^{(N_g)} v^{(N_g)}}{W} I^{(N_g)} L^{(N_g)}}{1 - \sum_{j=1}^{N_g} \frac{\rho^{(j)} R^{(j)} v^{(j)}}{W} I^{(j)}\left(1-\alpha^{(j)} + f_{DL}^{(j)}\right)}, \tag{11}$$

where $I^{(j)}$, $j=1,\ldots N_g$ are the number of RL connections in each user group and N_g is the number of user groups. The parameters with superscripted indexes are linear averages of the individual parameters among each user group.

Common channels with no dynamic power control can also be modelled either by adding a constant power to P already into Equation (3) or more optimally, by modelling each common channel as a user group in Equation (11), with one imaginary user locating at the cell edge.

If the number of users in a user group is high the linear averages of the parameters can be replaced by the expectation values with a small margin added but for high bit rate services with low number of simultaneous connections this would underestimate the required BS power too much giving only a long term average. One way to overcome this problem would be to use the worst case parameter values (cell edge) for the most demanding services. A more accurate method would be to form the distributions for the sum of parameters of 1,2,3... RL connections, after which appropriate quantiles should be chosen to ensure low enough blocking and dropping because of total BS power.

The accuracy of the presented model has been studied in [5] in which the downlink power budget using Equation (6) has been compared to results from a WCDMA radio network simulator.

III. Usage of the downlink pole equation

In Figures 1 and 2 there are two basic macro cell examples demonstrating the usage and consequences of the formulas of Chapter II.

In Figure 1 the required total BS transmission power has been plotted as a function of the number of speech users (12.2 kbit/s codec) per cell for different cell isolation scenarios, which are modelled by varying f_{DL} from 0.5 to 0.8. In reality f_{DL} depends on the propagation conditions and cell planning including antenna selection. The chosen range of f_{DL} is based on theory ([6]) and simulations in a regular hexagonal macro cell grid using three sectored cell configuration and Okumura-Hata propagation model with different values for a log-normal shadow fading. In Figure 1 the required E_b/N_0 was 8 dB and the orthogonality factor α was 0.5. These values correspond to link level simulations made with the ITU Vehicular A channel profile with UE speed of 50 km/h. Average SHO combining gain for the SHO connections (compared to single link) was 1 dB, channel activity factor was 0.67 (50% voice activity + dedicated control channel overhead), effective BS antenna gain was 15 dB, effective UE antenna gain was 0 dB, SHO overhead was 40% (based on simulations), UE noise power was −100 dBm, maximum supported propagation loss was 150 dB and peak to average propagation loss was 7 dB. Common channels were modelled in a simplified manner by doubling the common pilot channel with C/I requirement of −18 dB at the cell edge.

In Figure 2 the cell isolation was kept constant with $f_{DL} = 0.6$ but the maximum allowed propagation loss was varied from 140 dB to 155 dB. Other parameters were the same as in the case of Figure 1.

It can be seen clearly from Figures 1 and 2 how the required BS power depends on interference conditions and cell radius on the other hand. One can also see the difference whether the same BS transmission power is used for large cell range or high loading. In the latter case the system is more sensitive to traffic variations and mobility.

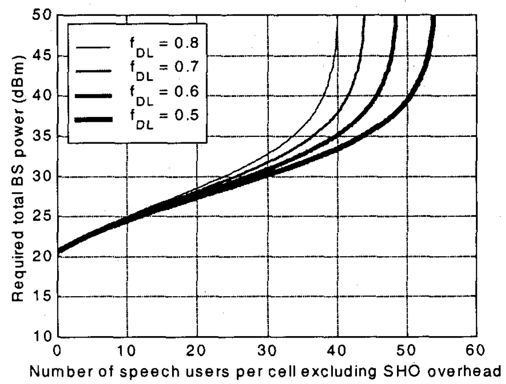

Figure 1. The required BS power in macro cells as a function of number of speech users (12.2 kbit/s codec) per cell for different other-to-own-cell interference ratios.

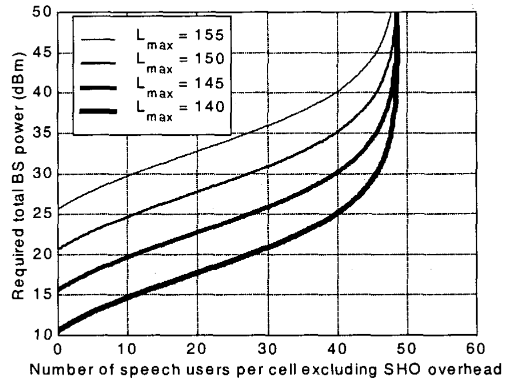

Figure 2. The required BS power in macro cells as a function of number of speech users (12.2 kbit/s codec) per cell for different cell ranges.

In Figure 3 there is yet another example which is similar to Figure 1 but the parameters correspond to a micro cellular network. In here the E_b/N_0 requirement is 8.4 dB, α is 0.75 which have been estimated by link level simulations with two Rayleigh fading propagation paths (equal gains in the average). Pathloss values were taken from a micro cell plan in the centre of Helsinki, in which the site density was 10 cells per km^2. Pathlosses were predicted by an accurate ray tracing based propagation tool which has been described in [7] and [8]. Maximum allowed propagation loss was 135 dB (95% quantile including buildings) and average propagation loss was 121 dB. It was assumed that the effective antenna gain of BS was 3 dB. The other-to-own-cell interference ratio f_{DL} was varied from 0.1 to 0.4. These values are clearly smaller than in the macro cell case of Figure 1. This is because of better isolation of cells due to low antenna height and building geometry. (The average f_{DL} calculated from the micro cell plan, by Equation (8), was 0.14.) Based on the steep cell boundaries and simulations in micro cell scenarios the SHO overhead was set 15%. Other parameters were the same as in the case of Figure 1.

Note that the number of users has been limited to 110 in Figure 3 due to limitation in the number of orthogonal codes (spreading factor = 128).

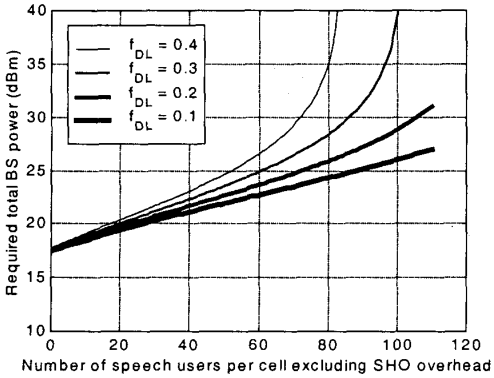

Figure 3. The required BS power in micro cells as a function of number of speech users (12.2 kbit/s codec) per cell for different other-to-own-cell interference ratios.

One can see from Figures 1 and 3 that with the chosen parameters the spectral efficiency in micro cells is about double the spectral efficiency in macro cells. Notice that analysing the downlink only in a pure speech traffic case (like in Figures 1, 2 and 3) is slightly theoretical since it is not clear whether uplink or downlink is the limiting direction. Uplink should be analysed simultaneously. Still, similar behaviour can be expected in the case of asymmetric services, where the downlink is more probably the limiting direction.

In Figure 4 the data capacity per cell for the micro cell case has been plotted as a function of cell isolation using 64 kbit/s (user bit rate) RL connections. In this case the E_b/N_o requirement was 6.9 and channel activity 1 but the other parameters were the same as in the case of Figure 3.

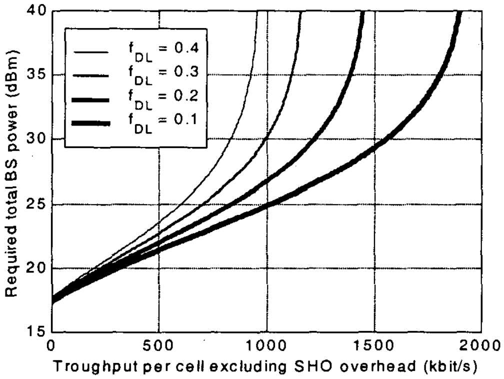

Figure 4. The required BS power in micro cells as a function of user data throughput per cell (64 kbit/s user data rate) for different other-to-own-cell interference ratios.

IV. Conclusions

It has been shown that the downlink capacity of a WCDMA network can be approximated by using a downlink pole equation which is analogous to the corresponding uplink pole equation. Furthermore the equation can be used in estimating the required total base station transmission power and the transmission power limits for individual channels, as common channels, speech channels and user data channels with different bit rates and quality requirements.

The method can also be used in radio network dimensioning when combined with uplink analysis. Dimensioning starts from the traffic requirements for different services. As the amount of hardware resources (code channels and maximum base station and user equipment transmission power) is hard limited and a certain uplink and downlink loading can be allowed to keep the system stable, it can be calculated how many cells per km^2 is required to meet the traffic requirements. Naturally this requires as input the path loss distribution as a function of site density.

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