The Downlink Orthogonality Factors Influence on WCDMA System Performance

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Abstract—**The large scale statistics of the downlink orthogonality factor (OF) is adressed in this paper for typical urban macro cellular environments for terminals with standard Rake receivers. It is found that the OF improves as the user moves closer to the BS and the OF is positively correlated with the shadow fading component of the radio channel. The mean value of the OF is typically larger for users dominated by own cell interference over other cell interference. These effects results in a larger excess capacity close to the BS, compared to scenarios where the OF is assumed to be constant within the cell.**

I. Introduction

Let us consider the downlink (DL) of a wideband code division multiple access (WCDMA) system, where signals transmitted from the same base station (BS) are separated by means of synchronized orthogonal codes. As orthogonal codes do not have white noise properties, the total transmitted signal from each BS is scrambled by a pseudo noise (PN) sequence, which is unique for each BS. This transmission scheme is applied for the UTRAN FDD system, where the orthogonal codes are derived from the set of Walsh codes, while the BS specific PN sequence is a Gold code [1]. Hence, in radio channels with no time-dispersion the own cell interference is completely eliminated after despreading. However, the orthogonality is partly destroyed in temporal dispersive radio channels because time-shifted versions of the orthogonal channelization codes are not orthogonal.

The effect of using orthogonal codes for own cell user separation in WCDMA systems has been addressed by DaSilva in [2]-[3], assuming a Rake receiver. Recently, the term *Orthogonality Factor* (OF) has been widely introduced and accepted as a measure of the degree of orthogonality between own cell signals received by a particular user. Note that in general the OF is different for each user in the system. The OF is an important and useful parameter for simple capacity assessments at system level [4], and radio network planning in general [5]. The basic behaviour of the average OF and its dependency on the temporal dispersion of the radio channel is discussed by Passerini in [6]. Experimental results on the OF, extracted from urban and rural field measurements are presented in [7]. The local statistics and time-variant behaviour of the OF is addressed in [8] as function of the resolvable multipath compoments phase and amplitude variations of standardized power delay profiles. In this study we investigate the large scale statistics of the OF, assuming single antenna transmission from the BS and a Rake receiver at the user. Thus, users with advanced receivers such as equalizers for improving the OF are not considered in this study and neither is scenarios with transmit diversity at the BS. In this context, large scale statistics refers to the probability density function (pdf) of the OF for all users in a cell, where the OF for each user is an average over the radio channel fast fading. In this analysis, we will focus on the OFs influence on the WCDMA system performance. In deriving the large scale statistics of the OF we use the stochastic delay spread model proposed by Greenstein [10].

The paper is organized as follows. The downlink OF is presented in Section II. Greensteins delay spread model is outlined in Section III. The results for the large scale statistics of the OF are presented in Section IV followed by a discussion of the impact of these results on WCDMA system performance in Section V. Concluding remarks are provided in Section VI.

II. The Downlink Orthogonality Factor

Using the downlink OF, the narrowband energy to interference plus noise ratio after Rake finger combining for a particular user can be approximated as [1]

$$\rho = \frac{R_c}{R_b}\frac{P_{user}}{P_{own}(1-\alpha)+P_{other}+P_{noise}}, \qquad (1)$$

where R_c is the chiprate, R_b is the bit rate, P_{user} is the received power of the desired signal, P_{own} is the total received wideband power from the own cell BS, P_{other} is the total received wideband power from other BSs, P_{noise} is the thermal noise, and $\alpha \in [0;1]$ is the DL OF. Hence, $\alpha = 1$ indicates that the orthogonality of the own cell signals is maintained at the receiver, while $0 \leq \alpha < 1$ corresponds to the case where the orthogonality is partly or fully destroyed. The term $(1-\alpha)$ is often referred to as the multipath loss factor of the radio channel [6]. We will assume that the OF is averaged over all combinations of channelization codes, so it does not depend on the number of active users and the transmit power per channelization code [8]. The OF is a function of the delay spread function of the downlink radio channel, which can be expressed in discrete form as

$$h(\tau) = \sum_{l=1}^{L} \beta_l \delta(\tau - \tau_l), \qquad (2)$$

[1] In writing (1) we implicitly assume that all signals from the own cell BS are transmitted under the same scrambling code, i.e. no secondary scrambling codes are enabled.

where β_l and τ_l is the complex amplitude and delay of the l-th multipath component, respectively. The number of multipath components is denoted L. For the sake of simplicity, we will assume that

$$|\tau_m - \tau_n| \geq T_c \ \forall \ m \neq n \tag{3}$$

$$|\beta_l| \geq |\beta_{l+1}|, \tag{4}$$

where $|\cdot|$ denotes absolute value and $T_c = 1/R_c$ equals the chip time, i.e. all the multipath components are resolvable by the Rake receiver. From (2) we can express the average power delay profile (PDP) of the radio channel,

$$P(\tau) = \sum_{l=1}^{L} \mathrm{E}\{|\beta_l|^2\}\delta(\tau - \tau_l), \tag{5}$$

where $\mathrm{E}\{\cdot\}$ denotes spatial averaging over the fast fading. The OF also depends on the number of active Rake fingers (M) and the Rake finger combiner weights[2]. A commonly used Rake finger combiner weight for the m-th Rake finger is [2]-[3]

$$w_m = \beta_m^* \quad \forall \, m \in [1, 2, \ldots, M], \tag{6}$$

where $[\cdot]^*$ denotes complex conjugate. Thus, the combiner weight in (6) is matched to the m-th multipath component. However, in the case where orthogonal codes are used for tranmission, the optimal combiner weight for the m-th Rake finger is given by

$$w_m = \frac{\beta_m^*}{P_{own}\sum_{l=1, l\neq m}^{L}|\beta_l|^2 + P_{other} + P_{noise}}. \tag{7}$$

Note that (7) corresponds to ideal maximal ratio combining (MRC), assuming that the thermal noise at each Rake finger is identical. It is important to emphasize that the OF will also depend on P_{own}, P_{other}, and P_{noise} if (7) is used. If (6) is used, the OF is only a function of $h(\tau)$ and M. However, the OF is reported to change less than 10% depending on whether the Rake finger weights in (6) or (7) are applied [8].

Detailed expressions of the instantaneous OF are derived in [8] for the case where either (6) or (7) is used. An approximate formula for the OF is presented in [6] and [8] for the case where it is averaged over the radio channel and $P_{own} >> P_{other} + P_{noise}$, i.e.,

$$\alpha = 1 - \left[\sum_{m=1}^{M} \frac{|\beta_m|^2}{\sum_{l=1, l\neq m}^{L}|\beta_l|^2}\right]^{-1}. \tag{8}$$

It is worth noticing from (8) that the phase averaged OF is only a function of the relative power of the resolvable multipath components and not dependent on the relative delay between the multipaths. Throughout this paper, we will assume that the number of Rake fingers (M) is selected so all resolvable multipath components within a window of 15 dB relative to the strongest path are tracked.

From a WCDMA system perspective, the importance of the OF depends on the interference ratio

$$G = \frac{P_{own}}{P_{other} + P_{noise}}. \tag{9}$$

Hence, for $G << 1$ the OF becomes less important for the value of ρ, while ρ becomes more dependent on the OF for $G >> 1$.

III. Delay Spread Model

There is a large body of results reported in the open literature that permits a statistical description of the PDP in different environments; see [9]-[13] among others. This allows us to further quantify the statistical behaviour of the OF. We will focus on outdoor typical urban macro cellular scenarios, where the BS antenna is mounted above rooftop level while the user is positioned in street canyons. A commonly accepted model of the RMS delay spread (DS) in such environments is Greensteins model [10], which suggests that (i) the local mean DS is lognormally distributed at any distance, (ii) the DS is negatively correlated with the radio channels shadow fading component, and (iii) the DS increases by the distance between the BS and the user. The DS at distance d between the BS and the user can therefore be expressed as

$$\sigma_\tau = T_1 d^\epsilon y, \tag{10}$$

where T_1 is the DS at distance $d = 1$ km, ϵ is a model parameter, and y is lognormal distributed random variable so $Y = \log_{10}(y)$ is Gaussian distributed with zero mean and standard deviation σ_y. The model has been validated by numerous independent measurement campaigns (see [11] among others) and recently adopted in the COST259 radio channel model [13]. The results presented in [11]-[13] furthermore suggests that the local PDP can be approximated with an exponentially decaying function for typical urban macro cellular environments, so

$$P(\tau) \propto \exp(-\tau/\sigma_\tau), \tag{11}$$

where $a \propto b$ reads a proportional to b. Assuming that $\tau_l = lT_c$, the large scale statistics of the OF can be obtained by combining (8), (10), and (11).

For typical urban macro cells, the model parameters are found to be in the range [10]-[13]: $T_1 \in [0.4; 1.1]$ μs, $\epsilon \in [0.5; 1.0]$, and $\sigma_y \in [2; 6]$ dB. The cross-correlation coefficient between the shadow fading component (expressed in decibel) and Y is typically found to be on the order of -0.7.

IV. Large Scale Statistics of the OF

A. OF versus RMS delay spread

Given the PDP in (11) the OF is plotted in Fig. 1 versus the DS. For this particular case it is observed that there is an approximate linear relationship between $\log_{10}(\alpha)$ and $\log_{10}(\sigma_\tau)$ for an exponentially decaying PDP. The change in the slope at $\sigma_\tau = 200$ ns is due to the change in the number of active Rake fingers. We will refer to the function in Fig. 1 as $\alpha = f(\sigma_\tau)$.

[2]In this context, the Rake finger combiner weight referes to the complex factor which is multiplied by the output of the Rake finger after despreading, before Rake combining

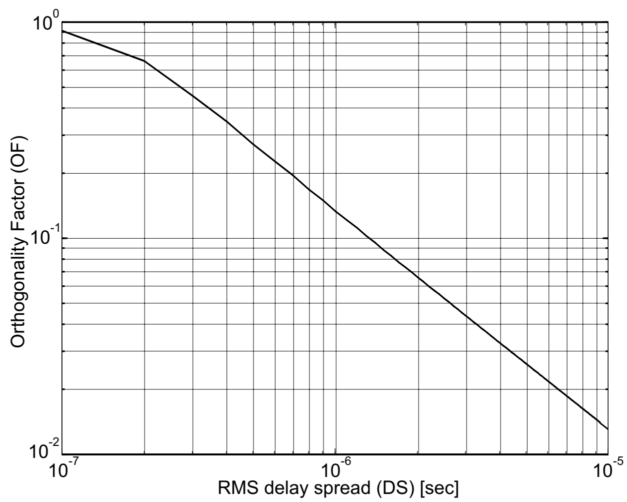

Fig. 1. OF versus the DS for an exponentially decaying PDP.

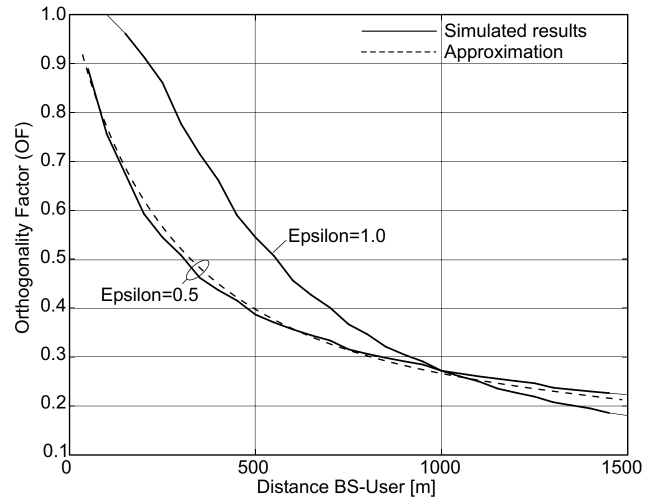

Fig. 2. The median OF versus the distance between the BS and the user.

B. Distance dependency

Using the distance dependent DS model, it is possible to plot the median value of the the OF versus the distance between the BS and the user. An example is shown in Fig. 2, where $T_1 = 0.5$ μs with $\epsilon = 1.0$ and $\epsilon = 0.5$. It is observed that the OF improves significantly as the user moves closer to the BS. Users in the close vicinity of the BS have $\alpha \simeq 1$, so the own cell interference is completed suppressed by the use of synchronized orthogonal codes. However, the model in (10) should be used with caution at small d, since the DS close to the BS typically reach a minimum value of 50-100 ns. To facilitate a simple description of the median OF at a given distance d, the following function

$$\overline{\alpha}(d) \simeq \frac{1}{1+kd}, \tag{12}$$

is found to provide a good match to the results in Fig. 2. For $\epsilon = 0.5$ the least square best fit is obtained for $k = 2.9$ (dashed line). The simplicity of (12) makes it easy to include the effect of distance dependt OF in link budget calculations, etc.

C. Correlation with shadow fading

The power of the desired user (P_{user}) and the own cell power (P_{own}) are propagated through the same radio channel and are therefore also subject to the same shadow fading component. This implies that during a shadow fade both P_{user} and P_{own} are attenuated with the same order of magnitude while the OF is likely to decrease due to the negative cross-correlation between the shadow fading and the DS (i.e., loss of orthogonality during a shadow fade). Contrary, a user on the cell edge is more likely to be connected to the BS with dominant shadow fading component and thereby also the BS which offers the best OF. The cross-correlation between $\log_{10}(\sigma_\tau)$ and the shadow fading component (expressed in decibel) of -0.7 [10]-[11] maps to a cross-correlation between $\log_{10}(\alpha)$ and the shadow fading component of 0.7, due the approximate linear relationship between $\log_{10}(\alpha)$ and $\log_{10}(\sigma_\tau)$ as shown in Fig. 1.

D. Cell pdf of the OF

As discussed in Section II the importance of the OF depends on G. We will therefore consider the pdf of the OF conditioned on $(G > x)$ experienced by users connected to the same cell, i.e.,

$$p(\alpha|G > x). \tag{13}$$

Given (13) let us define the central moments of the conditional pdf as

$$\mu_\alpha(x) = \int_0^1 \alpha p(\alpha|G > x) d\alpha \tag{14}$$

and

$$\sigma_\alpha^2(x) = \int_0^1 [\alpha - \mu_\alpha(x)]^2 p(\alpha|G > x) d\alpha. \tag{15}$$

We extract (13) from Monte-Carlo simulations assuming a standard network topology with three sector BSs as illustrated in Fig. 3. Each BS is equipped with three 65 degree antennas and a front-to-back ratio of 20 dB. The distance between BSs is fixed at 1.5 km so the approximate radius of each hexagon equals 0.5 km. The distant dependence pathloss between each user and BS is is calculated from a simple single-slope model with a pathloss exponent of 3.6. The standard deviation of the lognormal distributed shadow fading component is 8.0 dB and assumed uncorrelated in the links from different BSs towards the same user and fully correlated between sectors on the same BS. The cross-correlation coefficient between the shadow fading component and Y equals -0.7, $\epsilon = 0.7$, and $\sigma_y = 4$ dB. Users are assumed to be uniformly distributed in the network and connected to the sector on the BS which corresponds to minimum pathloss (incl. the shadow fading component). All sectors are assumed to transmit with equal power. Statistics is collected from one center cell, simulating the two surrounding tires of cells to obtain the correct G-factor statistics.

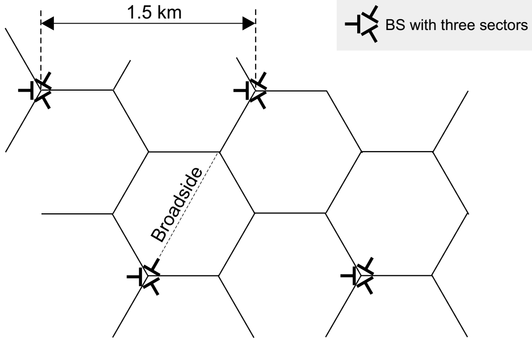

Fig. 3. Standard cell layout with three sector BSs.

The pdf of the OF is plotted in Fig. 4 for $T_1 = 1.0$ μs and $T_1 = 0.5$ μs, assuming $x = 0$. The pdf for $T_1 = 1.0$ μs is more concentrated at lower values of the OF while the pdf for $T_1 = 0.5$ μs provides a larger spread of values. The presented results clearly indicate that the experienced OF varies significantly among the users in the cell. For comparison, measurements of the OF in a large urban cell at 27 different user locations is reported to have a mean OF of 0.5 and a standard deviation of 0.2 [7]. The measurements in [7] are mainly collected from users located at the cell edge, approximately 1.5 km from the BS. Modeling of the OF within a cell with a constant value is therefore a major simplification which may lead to unrealistic results.

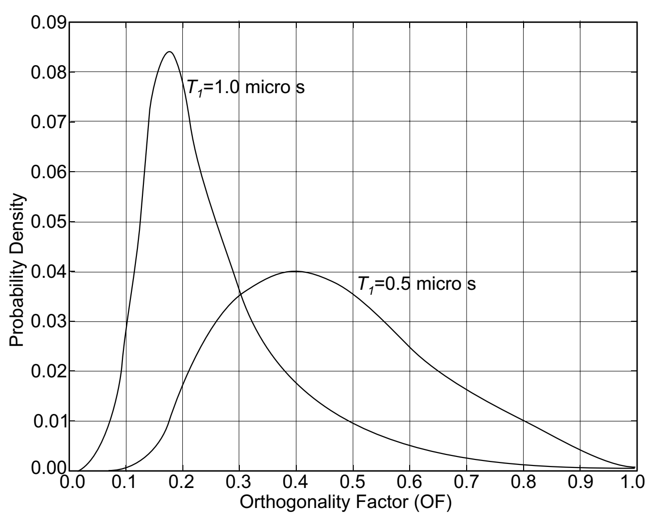

Fig. 4. Probability density function of the OF experienced by users uniformly distributed in a cell (x=0).

Fig. 5 pictures the conditional moments of the OF. As expected, the mean of the OF increases as function of x so users with a high G-factor generally experience a higher OF. This behaviour is mainly contributed by two effects; (i) Users with a high G-factor are more likely to be closely located to the serving BS and therefore experience a larger OF according to (12) and (ii) users with a constructive shadow fade tend to have a larger OF and G-factor. The trends in Fig. 5 are favourable from a WCDMA system perspective, since a high OF mainly is needed for larger values of G while the actual value of the OF for small G becomes less important. The simulation results show that approximately 14% of the users experience $10\log_{10}(G) > 10$ dB while 46% have $10\log_{10}(G) > 0$ dB. The cross correlation coefficient between $\log_{10}(G)$ and the OF over the entire cell is found to equal 0.61.

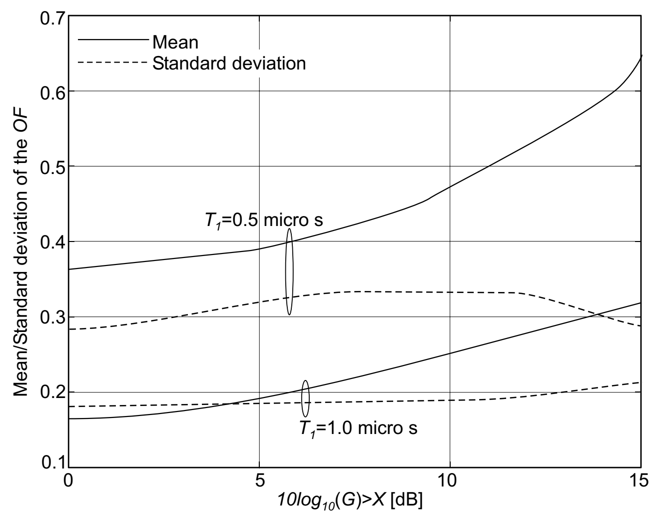

Fig. 5. Mean and standard deviation of the conditional pdf of the OF within a cell.

V. System Aspects

The downlink cell capacity of a WCDMA system depends on the required E_b/N_0 of the users, the total available transmit power, the G-factor distribution of the users, and the noise level. However, the capacity is also a function of the joint distribution of the OF and G, as demonstrated in [4] where an expression for the downlink load factor is derived. In order to further illustrate how the OF influences the performance of WCDMA systems, we will consider the offered bit rate to a user, who is moving from the cell edge towards the BS. This is a very simple example where the user is assumed to be moving along the trajectory described by the broadside direction of the antenna in the cell (dashed line in Fig. 3). Given these assumptions, the offered bit rate to the user as a function of the distance to the BS (d) is obtained by re-arranging (1),

$$R_b(d) = \frac{R_c/\rho P_{user}(d)}{P_{own}(d)[1-\alpha(d)] + P_{other}(d) + P_{noise}}. \quad (16)$$

The relative offered bit rate compared to the distance r, assuming a constant OF is expressed as,

$$Q = \frac{R_b(d)}{R_b'} \quad (17)$$

with

$$R_b' = \frac{R_c/\rho P_{user}(r)}{P_{own}(r)[1-\alpha'] + P_{other}(r) + P_{noise}}, \quad (18)$$

where α' is a constant OF. The power levels $P_{user}(d)$, $P_{own}(d)$, and $P_{other}(d)$ at distance d are computed via simulations, assuming the cell topology in Fig. 3. In these calculcations the shadow fading and fast fading is disabled, $y = 1$, and the transmit power towards the user is assumed constant so $P_{user}(d)$ only varies due to the deterministic distant dependent pathloss. The results are reported in Fig. 6 for $T_1 = 0.5\ \mu$s, $\epsilon = 0.5$, $\alpha' = f(0.50\ \mu s)$, $\alpha' = f(0.25\ \mu s)$, and $\alpha' = f(0.13\ \mu s)$, where $f(\cdot)$ is the function reported in Fig. 1. The corresponding G-factor is plotted in Fig. 7. It is observed that the relative offered bit rate increases as the user moves closer to the BS due to the larger value of G as shown in Fig. 7. The results of the distance dependent OF show that relative offered bit rate increases by a factor of 19 at $d = 100$ m, compared to $d = 1000$ m.

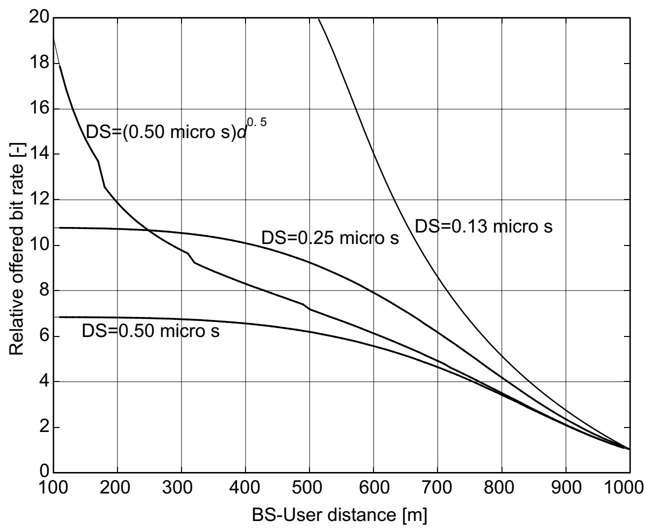

Fig. 6. Relative offered bit rate as a function of the distance betweeen the BS and the user.

The results for the distance dependent OF and $\alpha = f(0.25\ \mu s)$ will most likely result in the same average bit rate within the cell, assuming that users are uniformly distributed and served equally. However, if more advanced packet scheduling schemes are studied where users in favorable conditions (high G and α) are served more frequently, then the results for the distance dependent OF and $\alpha = f(0.25\ \mu s)$ will deviate significantly. This further underline the importance of modeling the behavior of the OF correctly.

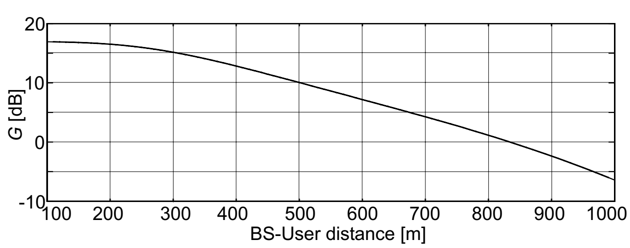

Fig. 7. G-factor as a function of the distance betweeen the BS and the user.

VI. Concluding Remarks

The downlink OF is an important metric for simple capacity assessments of WCDMA systems, link budget calculations, and radio network planning. It is found that the OF tends to improve as the user moves closer to the BS. The OF is positively correlated with the radio channels shadow fading component, so the orthogonality is likely to be degraded during a deep shadow fade. Simple examples are provided in order to demonstrate the importance of modeling large scale statistics of the OF correctly to obtain realistic results.

However, it should be emphasized that when the OF degrades, the potential gain from Rake finger diversity increases. The trade-off between a good OF and improved Rake finger diversity has not been addressed in this study.

References

[1] H. Holma, A. Toskala (Editors), "WCDMA for UMTS - Radio Access for Third Generation Mobile Communications", John Wiley and Sons, Second Edition, 2000.

[2] V. DaSilva, E.S. Sousa, "Performance of Orthogonal CDMA Codes for Quasi-Synchronous Communication Systems", *IEEE Proc ICUPC*, pp. 995-999, 1993.

[3] V. DaSilva, E.S. Sousa, "Performance of the Forward Link of a CDMA Cellular Network", *IEEE Proc. of International Symposium on Spread Spectrum Techniques and Applications*, pp. 213-217, 1994.

[4] K. Sipila, Z.C. Honkassalo, J. Laiho, A. Wacker, "Estimation of Capacity and Required Transmission Power WCDMA Downlink Based on a Downlink Pole Equation", *Proc. IEEE Vehicular Technology Conference,* pp. 1002-1004, May 2000.

[5] J. Laiho, A. Wacker, T. Novosad (Editors), "Radio Network Planning and Optimization for UMTS", John Wiley & Sons, 2002.

[6] C. Passerini, G. Falciasecca, "Correlation between delay-spread and orthogonality in urban environments", IEE Electronics Letters, vol. 37, no. 6, pp. 384-385, March 2001.

[7] M. Humukumbure, M. Beach, B. Allen, "Downlink orthogonality factor in UTRA FDD systems", *IEE Electronics Letters*, vol. 38, no. 4, pp. 196-197, February 2002.

[8] N.B. Mehta, L.J. Greenstein, T.M. Willis, Z. Kostic, "Analysis and Results for the Orthogonality Factor in WCDMA Downlinks", *IEEE Proc of Vehicular Technology Conference*, pp. 100-104, May 2002.

[9] D.C. Cox, "Distributions of multipath delay spread and average excess delay for 910 MHz urban mobile radio paths", *IEEE Trans. on Antennas and Propagation*, vol. AP-23, pp. 206-213, March 1975.

[10] L. J. Greenstein, V. Erceg, Y.S. Yeh and M. V. Clark, "A new path-gain/delay-spread propagation model for digital cellular channels," *IEEE Trans. on Veh. Technol.*, vol. 46, no. 2, pp. 477-485, May 1997.

[11] A. Algans, K.I. Pedersen, P.E. Mogensen, "Experimental Analysis of the Joint Statistical Properties of Azimuth Spread, Delay Spread, and Shadow Fading", *IEEE Journal on selected areas in communications*, vol. 20, no. 3, pp. 523-531, April 2002.

[12] COST-207, "Information Technologies and Sciences - Digital Land Mobile Communications", *Commission of European Communities*, September 1988

[13] L. Correia (Editor), "Wireless Flexible Personalised Communications - COST 259 Final Report", *John Wiley & Sons*, May 2001.