Performance Analysis Of A Single UMTS Cell

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Abstract

Performance analysis of multi service UMTS networks is of major interest for mobile network providers. Because of the W-CDMA technique used in UMTS, which leeds to an interference limited system with a dynamic cell capacity and load dependent cell coverage, the service mix has a big influence on the system performance. The aim of this paper is to provide a detailed description of the performance relevant mechanisms for the uplink of a single UMTS cell and to extract capacity bounds for single and multi service operation. We propose a simplified calculation model for the multi service case, based on the number of users of different radio link services.

1 Introduction

The introduction of the "Universal Mobile Telecommunication System" UMTS as a standard for third generation mobile networks promisses circuit and packet switched mobile access with fair data rates. In addition to traditional voice communication this system enables a wide range of new data services including mobile Internet. It is not yet clear how this service mix will look like in real UMTS systems and therefore, it is difficult for network providers to forecast the actual system capacity. This paper provides a detailed description of the performance relevant mechanisms for the uplink of a single UMTS cell and extracts capacity bounds for single and multi service operation.

The radio access technology used in UMTS is asynchronous "Wideband Code Division Multiple Access" (W-CDMA). In such a system the power is the common shared resource for users [1]. W-CDMA uses a set of spreading sequences or codes with optimal correlation characteristics. The interference depends on this correlation, and increases with the number of multiplexed data streams. This leeds to an interference limited system with a dynamic cell capacity and load dependent cell coverage [1, 2]. Due to the requested signal to noise ratio the number of streams will typically be fewer than the number of available codes. Regarding this, the service mix has a big influence on the system performance and has to be taken into account for the investigations of UMTS systems.

The rest of the paper is organized as follows. First, a detailed description of the uplink of a single UMTS cell is given, regarding performance aspects. Then we extract capacity bounds for single and multi service operation, trying apply realistic assumptions. We propose a simplified calculation model for the multi service case, based on the number of users of different radio link services. Finally, we conclude and give an outlook for further investigations.

2 System Description

In CDMA systems like UMTS, the scarce resource is the transmission power. Talking about the Frequency Division Duplex mode (FDD) of UMTS, the power budgets for uplink and downlink are independent of each other. While the uplink power budget is limited by the transmission power of each User Equipment (mobile station), the downlink power budget depends only on the capabilities of the Node B (base station). The following investigations will focus on the uplink power budget.

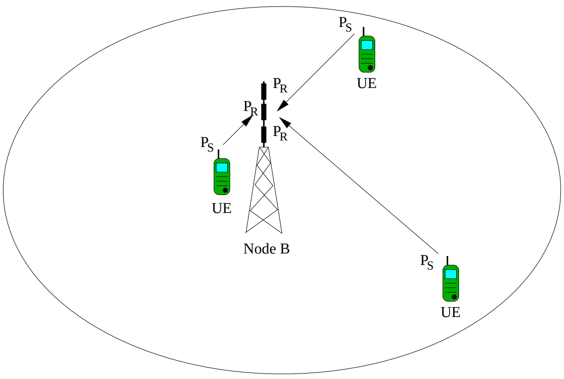

Figure 1. UMTS cell

Figure **1** demonstrates the situation in a single UMTS cell for uplink transmission. Each user transmits data with a certain transmission power P_S (measured at the UE antenna). At Node B (base station) the signals arrive with a smaller power P_R, because of path losses. Assuming ideal free space propagation of the radio signal the following condition holds [3]:

$$P_R = P_S \cdot \left(\frac{\lambda}{4\pi d}\right)^2 \cdot g_b \cdot g_m \qquad (1)$$

where d is the distance between User Equipment and Node

B, λ is the carrier wavelength and g_b and g_m are the power gains of the Node B antenna and mobile equipment antenna, respectively.
According to the CDMA mechanism, the signals arriving at Node B are separated using coding techniques. Because of the non ideal orthogonality of the codes, the signals of other users generate a noise level which is called interference. The interference I seen at Node B for the user i signal is the sum over the received power of all other users j multiplied with an interference factor ϵ_{ij}, which represents the non-ideal orthogonality. There is also a basic noise level N_0, mainly the interference from other UMTS cells, which has to be taken into account.

$$I_i = N_0 + \sum_{\forall j \neq i} P_{Rj} \cdot \varepsilon_{ij}$$

For flexible bitrate adaption UMTS is using spreading techniques with variable spreading factor codes. Data symbols to be transmitted are spread over a certain number of chips, which are the basic channel symbols of UMTS. The spreading factor SF represents the number of chips a single data symbol is spread on. Because of the spreading technique there is a spreading gain for the received power at Node B. The more chips a data symbol is spread on, the higher is the spreading gain, but the lower is the data symbol rate. Taking the spreading gain into account, the received power after de-spreading, called C, is the received power P_R at Node B multiplied with the spreading factor SF for each user i.

$$C_i = SF_i \cdot P_{Ri}$$

Figure **2** summarizes the power situation at Node B according to the example given in figure **1**.

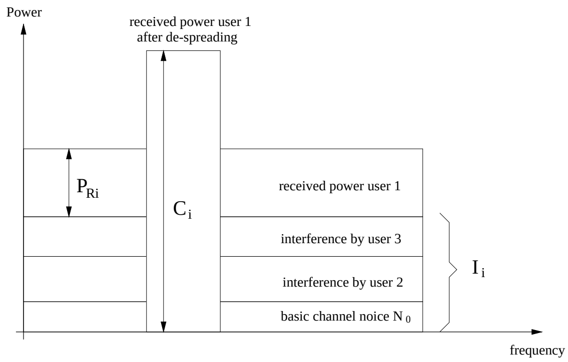

Figure 2. Power budget at Node B

For decoding the signals at Node B with a given bit error ratio (BER) a certain signal to noise ratio (SNR) has to be reached for each user signal. The actual value of SNR is service dependent and is based on the used modulation technique, forward error correction scheme and the desired bit error ratio. For the investigated CDMA system the signal to noise ratio for a certain user signal i at Node B can be approximated to be the ratio of the received power after despreading, C_i, and the interference I_i caused by the other user signals.
Therefore, as a global condition for the entire UMTS cell it can be stated that for each active user within this cell the following relation must hold [4]:

$$SNR_i \leq \frac{C_i}{I_i} = \frac{SF_i \cdot P_{Ri}}{N_0 + \sum_{\forall j \neq i} P_{Rj} \cdot \varepsilon_{ij}}$$

For the ongoing investigations, we assume perfect power control. This leads to a behaviour, where the system is always able to exactly provide the desired SNR_i for every signal of user i. This is a quite strong assumption probably not to be reached in real systems. Nethertheless, power control is one of the most important tasks in CDMA systems and the UMTS standard defines a power control performed 15 times within a single radio link frame of 10 ms. Therefore, perfect power control can be assumed for investigations on a larger timescale. Dealing with a number of n active users within the UMTS cell, this leads to the following global condition:

$$SNR_i = \frac{SF_i \cdot P_{Ri}}{N_0 + \sum_{\forall j \neq i} P_{Rj} \cdot \varepsilon_{ij}} \qquad for \;\; i, j = 1...n$$

Introducing a service factor S_i,

$$S_i = \frac{SF_i}{SNR_i}$$

which combines the service dependent UMTS radio parameters the following linear system of equations is obtained:

$$N_0 = S_i \cdot P_{Ri} - \sum_{\forall j \neq i} \varepsilon_{ij} \cdot P_{Rj} \qquad for \;\; i, j = 1...n \quad (2)$$

Using matrix notation the power conditions for all user signals arriving at Node B of the considered UMTS cell can be described as follows:

$$\mathbf{N} = (\mathbf{S} - \mathbf{E}) \cdot \mathbf{P_R} \quad (3)$$

with $\mathbf{N} = (N_0, ..., N_0)^T$ as the noise vector of dimension n, the diagonal matrix $\mathbf{S} = \mathbf{diag}(S_1, ..., S_n)$ of dimension (nxn), the power vector $\mathbf{P_R} = (P_{R1}, ..., P_{Rn})^T$ and the interference factor matrix $\mathbf{E}$ with the following structure:

$$\mathbf{E} = \begin{pmatrix} 0 & \varepsilon_{12} & \cdots & \varepsilon_{1n} \\ \varepsilon_{21} & 0 & \cdots & \varepsilon_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \varepsilon_{n1} & \varepsilon_{n2} & \cdots & 0 \end{pmatrix}$$

Having knowledge on the value of N_0, the service specific parameters SF_i and SNR_i for every user in the cell and the interference factor ε_{ij} for each code combination, the linear system of equations can be solved. It results in a certain power level P_{Ri} that has to be reached at Node B for each user signal i. The limitations due to the maximum number of users within the cell and the distance between the user and Node B will be discussed in the next section.

3 Capacity Analysis

3.1 Single Service Case

The single service case holds, if all user signals are transmitted with the same spreading factor SF_i and equal desired SNR_i for all the users. Therefore S_i is also equal for all active users i within the considered cell.

Furthermore, we assume the interference factors ε_{ij} to be equal for all code combinations. Because in the single service case each user signal uses the same spreading factor SF this assumption seems to be realistic. With

$$S_i = \frac{SF_i}{SNR_i} = S \qquad for \;\; i = 1...n$$

$$\varepsilon_{ij} = \varepsilon \qquad for \;\; all \;\; i \neq j$$

equation (2) can be written as

$$N_0 = S \cdot P_{Ri} - \varepsilon \cdot \sum_{\forall j \neq i} P_{Rj} \qquad for \;\; i,j = 1...n$$

resulting in the fact that the received powers P_{Ri} at Node B are equal for all user signals i.

$$P_{Ri} = P_R \qquad for \;\; i = 1...n$$

Assuming n users within the considered cell all using the same radio service, this leads to the following global condition for the received power levels $P_{Ri} = P_R$ at Node B:

$$N_0 = P_R \cdot (S - \varepsilon \cdot (n-1)) \tag{4}$$

There are two conditions defining capacity bounds for the uplink. One is due to the interference level at Node B, which increases with the number of active users. The other is due to the limited sending power of the User Equipment. It may not be able to send with enough power to reach Node B with the required received power level P_R because of path loss. The following subsections describe these effects in detail and extract the capacity bounds.

3.1.1 Capacity limits due to interference

As explained in the previous section, each active user generates a certain interference level for all the other users. The more users entering the cell, the more increases the interference level seen by a certain user i and, therefore, the more received power this user must provide. Because of the linear relationship between the received power P_R of user i and the resulting interference level for all the other users, the system is no longer able to improve the signal to noise ratio (SNR) by increasing the received power if the number of users in the cell reaches a certain limit, which is given through the condition:

$$S > \varepsilon \cdot (n-1)$$

This inequation defines the capacity bound of a single service UMTS system due to the interference caused maximum number of active users. As it can be seen, the maximum number of users only depends on the interference factor ε and the service descriptor S, which is the ratio of SF to SNR.

According to the inequation:

$$n_{max} < \frac{S}{\varepsilon} + 1$$

figure **3** visualizes the results for different ε values. Assuming a given SNR of $3dB$, the vertical dotted lines indicate the corresponding S values for the spreading factors $SF = [4, 8, 16, 32, 64, 128, 256]$. For $\varepsilon = 0.7$ this results in an interference caused maximum number of users $n = [3, 6, 12, 23, 46, 92, 183]$, respectively.

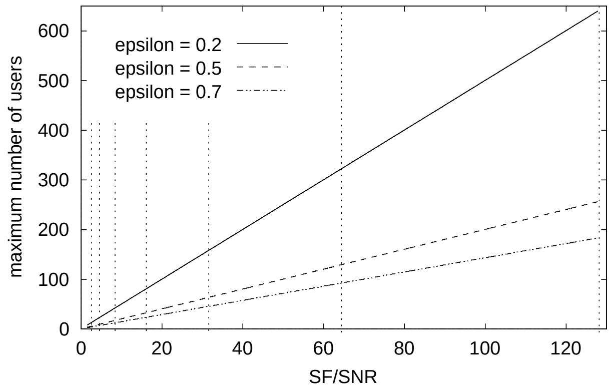

Figure 3. Interference caused maximum number of users

3.1.2 Capacity limits due to limited uplink power

The second reason for capacity constraints of the uplink is the limitated transmission power P_S of the User Equipment. Depending on the distance d between UE and Node B, the UE may not be able to provide the desired received power P_R at Node B due to path losses. Assuming a maximum transmission power P_{Smax} for each UE the maximum distance d_{max} can be calculated according to (1) as:

$$d_{max} = \frac{\lambda}{4\pi} \cdot \sqrt{\frac{P_{Smax}}{P_R} \cdot g_b \cdot g_m} \tag{5}$$

As already shown, the desired received power P_R at Node B depends on the number of users within the cell. Therefore, the maximum distance d_{max} between UE and Node B will also be a function of the number of active users. This means, for each additional user, the border, where an user can just be covered, will move closer to Node B and, therefore, the maximum possible area of coverage decreases. Figure **4** demonstrates this behaviour.

For the single service case the received power P_R depending on the number of users n can be derived from (4). Assuming the antenna gains g_b and g_m to be 1, the maximum distance between UE and Node B is:

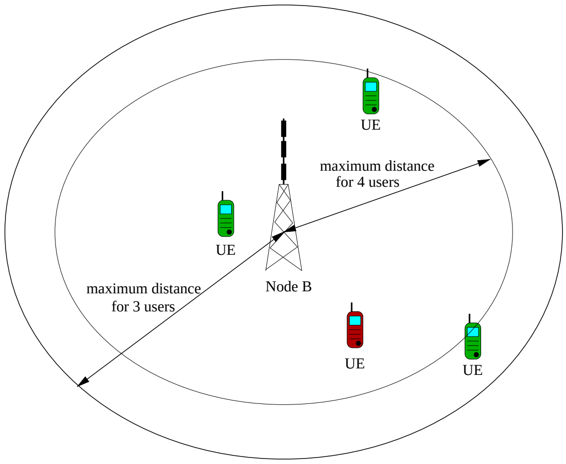

Figure 4. Maximum distance between UE and Node B

$$d_{max} = \frac{\lambda}{4\pi} \cdot \sqrt{\frac{P_{Smax}}{N_0} \cdot (S - \varepsilon (n-1))}$$

Figure **5** visualizes the results of this equation for different service factors S based on the following parameters: $P_{Smax} = 125mW$, $N_0 = -90dBm$, $\varepsilon = 0.5$ and $\lambda = 0.15m$ (which corresponds to a carrier frequency of 2 GHz).

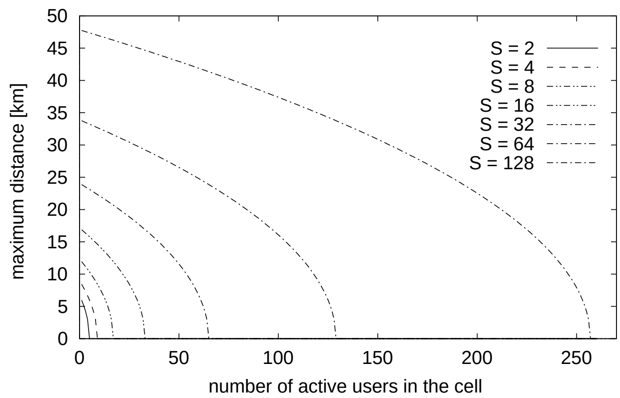

Figure 5. Maximum distance between UE and Node B

3.1.3 Single service uplink cell capacity

Mobile network providers will not base there cell planning on variable cell sizes, but on the coverage of a given area by one cell. Therefore, it is essential to know the maximum number of active users depending on the choosen cell size and the radio link service. This combines the two capacity limitations described in the previous subsections.

If we state the cell to cover an ideal circle with the cell radius r and assuming furthermore, that some of the users, which we want to cover, are located close to the cell border, the maximum number of active users within a single UMTS cell can be calculated to:

$$n_{max} = \left(\frac{S}{\varepsilon} - \frac{N_0 \cdot (4\pi r)^2}{\varepsilon \cdot P_{Smax} \cdot \lambda^2} \right) + 1$$

Note that negative values for n_{max} indicate capacity constraints due to the limited uplink power and users at the cell border are not covered anymore. Figure **6** visualizes the results for different service factors S based on the following parameters: $P_{Smax} = 125mW$, $N_0 = -90dBm$, $\varepsilon = 0.5$ and $\lambda = 0.15m$.

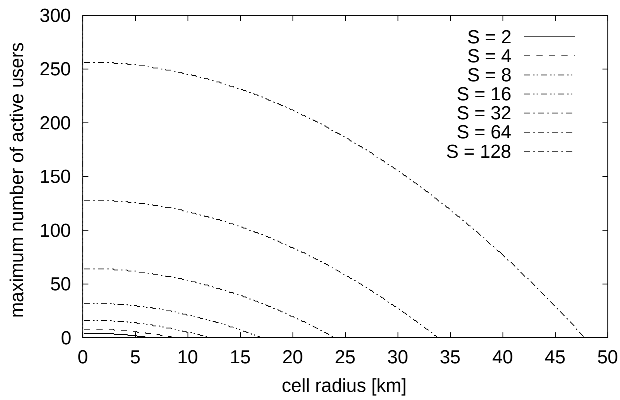

Figure 6. Uplink capacity of a single UMTS cell

3.2 Multi Service Case

The multi service case is characterized by the request for different radio link services k. Different spreading factors SF as well as other signal to noise ratios SNR may be requested, resulting in different service parameters S_k.

Generally, also for the multi service case the received power levels P_{Ri} required at Node B can be calculated for all users i using (3). Nevertheless, for an increasing number of users the mentioned linear equation system becomes more complex. In the following we propose a simplified calculation model, based on the number of users of different radio link services.

Let n_k be the number of users requiring the same radio link service k and, therefore, having identical S_k values. We further assume the interference factors ε_{ij} to be equal between all user signals i and j using the same service parameter S_k. The so defined intra class interference factor is named ε_{kk}. In addition the ε_{ij} between all users i of service k and all users j of service l are assumed to be identical too, described by inter class interference factors ε_{kl}.

Taking the fact into account, that the received power P_{Ri} required at Node B is equal for all user signals using the same service factor S_k and having an identic interference factor ε_{kk}, the linear equation system (2) can be written as:

$$N_0 = S_k P_{Rk} - (n_k - 1)\,\varepsilon_{kk} P_{Rk} - \sum_{\forall l \neq k} n_l \varepsilon_{kl} P_{Rl}$$
$$for \;\; k, l = 1...s$$

where s is the number of different radio link service types k.
Using matrix notation the power conditions for the user signals of s different service types can be written as follows:

$$\mathbf{N} = (\mathbf{S} + \mathbf{E_D} - \mathbf{E} \cdot \mathbf{U}) \cdot \mathbf{P_R} \qquad (6)$$

with $\mathbf{N} = (N_0, ..., N_0)^T$ describing the noise vector and the power vector $\mathbf{P_R} = (P_{R1}, ..., P_{Rs})^T$ both of dimension s, the diagonal matrices $\mathbf{S} = \mathbf{diag}(S_1, ..., S_s)$ and $\mathbf{U} = \mathbf{diag}(n_1, ..., n_s)$ of dimension (sxs) describing service parameter and number of users of each service class and the interference factor matrices $\mathbf{E_D} = \mathbf{diag}(\varepsilon_{11}, ..., \varepsilon_{ss})$ and $\mathbf{E}$ with the following structure:

$$\mathbf{E} = \begin{pmatrix} \varepsilon_{11} & \varepsilon_{12} & \cdots & \varepsilon_{1s} \\ \varepsilon_{21} & \varepsilon_{22} & \cdots & \varepsilon_{2s} \\ \vdots & \vdots & \ddots & \vdots \\ \varepsilon_{s1} & \varepsilon_{s2} & \cdots & \varepsilon_{ss} \end{pmatrix}$$

3.2.1 Capacity limits due to interference

As already dicussed for the single service case, the number of active users is generally limited due to interference. The maximum number of users depends on the interference factors ε and the requested service classes. The capacity bound is exceeded if for any service class k:

$$S_k \leq -\varepsilon_{kk} + \sum_{l=1}^{s} n_l \cdot \varepsilon_{kl}$$

Considering $s = 3$ different service classes $k = (1, 2, 3)$ which request the service factors $S = (8, 32, 128)$ and assuming the interference factors $\varepsilon_{kl} = 0.5$ for all service classes k and l, figure **7** shows the maximum number of active users.

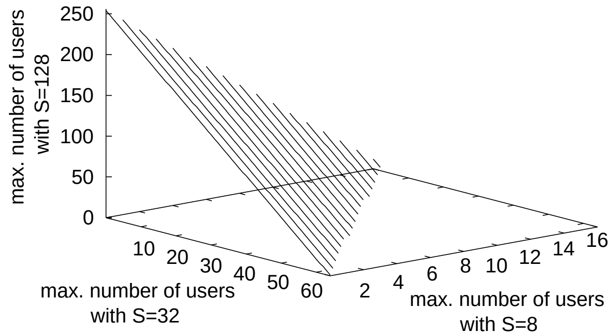

Figure 7. Interference caused maximum number of users

3.2.2 Capacity limits due limited uplink power

The capacity constraints caused by the limited transmission power P_{Smax} of the User Equipments is similar to the single service case. Knowing the received power P_{Rk} required at Node B for each service class k, the maximum distance between UE and Node B can be calculated using (5). Because the P_{Rk} will be different for each service paramter S_k, the maximum distance depends on the choosen service class. Figure **8** illustrates the situation.

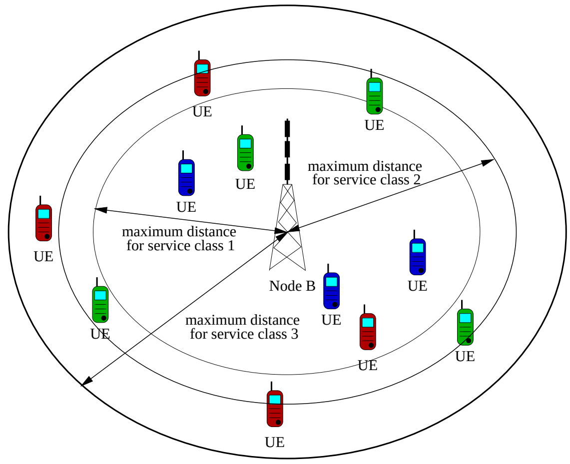

Figure 8. Maximum distance for different services

3.2.3 Multi service uplink cell capacity

For a given cell topology, which we assume to be an ideal circle of radius r, the maximum number of active users of each service class can be calculated combining (6) and (5). Assume the cell to cover all users of all service classes within the given area, the service class with the lowest value $S_{min} = min(S_1, ...S_s)$ of the service parameters will define the capacity limit.
Varying the number of users of each service class, the following condition must hold not to exceed the capacity limit:

$$d_{max}(S_{min}) \geq r$$

Figure **9** visualizes the results for different cell radii based on the following parameters: $S = (8, 32, 128)$, $P_{Smax} = 125mW$, $N_0 = -90dBm$, $\varepsilon_{kl} = 0.5$ and $\lambda = 0.15m$.

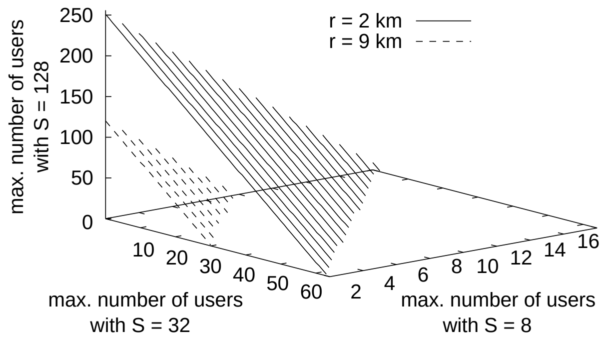

Figure 9. Uplink capacity with multi services

4 Conclusion and Outlook

In the paper the capacity bounds for the uplink of a single UMTS cell has been derived for single and multi service operation. The results show that the capacity is limited on one hand by the interference at Node B and on the other hand by the maximum possible transmission power of the User Equipments. Depending on the interference from other UMTS cells, included in the parameter N_0, the system is more or less sensitive to one of this aspects. Also, the capacity bounds are strongly depend on the used radio link services and there mix, characterized by S.
More knowledge on the correlation properties of the spreading codes resulting in more realistic ε values, can improve the shown results. Further investigations will focus on it.
A detailed description of the downlink situation and connection admission policy is already in progress. The modeling of the user services, resulting in an analytical burst level model using a multidimensional Markov chain is the aim of this work. It will allow to evaluate different call admission policies by comparing burst blocking probabilities and system utilization. Finally, we will compare the results with investigations done for GPRS [5, 6].

References

[1] E. Dahlmann, P. Beming, J. Knutson, F. Ovesjö, M. Persson, and C. Roobol, "WCDMA-the radio interface for future mobile multimedia communications," *IEEE Transactions on Vehicular Technology*, pp. 1105–1118, November 1998.

[2] F. Adachi, M. Sawahashi, et al., "Wideband DS-CDMA for next-generation mobile communications systems," *IEEE Communications Magazine*, pp. 56–69, September 1998.

[3] W. C. Jakes, ed., *Microwave Mobile Communications*. IEEE Press, 1974. ISBN 0-7803-1069-1.

[4] M. R. Garcia, J. E. B. Lati, J. M. R. Jerez, and A. D. Estrella, "Capacity analysis of a wideband CDMA system," in *Proceedings of XVII WTC Birmingham*, 2000.

[5] K. Begain, M. Ermel, T. Müller, J. Schüler, and M. Schweigel, "Analytical comparison of different GPRS introduction strategies," in *Proceedings of ACM MSWiM*, 2000.

[6] K. Begain, M. Ermel, T. Müller, J. Schüler, and M. Schweigel, "Analytical call level model of a GSM/GPRS network," in *Proceedings of SPECTS*, 2000.

Biography

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