

# On Modelling Spatial Traffic and Service Non-Uniformities in WCDMA Reverse Link

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**Abstract**— This paper focuses on the modelling of the reverse link of a WCDMA system in a non-homogeneous environment. Multiple traffic spatial and service non-uniformities are considered in the analytical model, then deriving expressions for required transmitted power and the associated outage probability. Special attention is also paid to the effect caused by different transmission bit rates and the spatial location of the traffic non-uniformities. The performance of the system is determined by QoS parameters, so that QoS may be controlled by setting an appropriate threshold. Such a threshold may be obtained by means of expressions found out throughout the paper.

**Keywords:** WCDMA, Non-uniformities, Traffic distribution, Service distribution, load factor, WCDMA capacity.

## I. INTRODUCTION

One of the main traffic characteristics in cellular networks is the non-homogeneous traffic spatial distribution. To cope with this inherent aspect in mobile communication scenarios, system deployment must be preceded by careful network planning. Network planning takes into account the expected traffic load all over the service area in order to come up with a solution on how many base stations are required and what are the suitable locations to set up the sites. Certain operator's objectives in coverage, capacity and quality must be met in the planning exercise. Furthermore, in the context of multimedia services, traffic needs to be detailed also in terms of traffic class spatial distribution (e.g. expected conversational traffic, interactive traffic, etc.) because of the different QoS requirements.

Nevertheless, although network planning can consider these non-homogeneities at some extent, the high dynamics associated to traffic generation processes coupled with user's mobility clearly need additional mechanisms to cope with the potential problems on the network performance derived from traffic profile distributions significantly different from those expected in the network planning phase. Traffic level and service mix variations along time and space, thus resulting in different load levels in different cells and times, may result in an observed QoS significantly different from the planned values, then negatively impacting in user's mobile experience.

In the context of WCDMA systems, service and traffic spatial distributions become even more important, since there is a tight dependence of the interference level observed on every

user's position in the network and the corresponding transmitted power levels. Clearly, the research community has already targeted these aspects. First approaches may be found in [1] and [2], where the impact of certain traffic distributions is analysed by means of simulations and analytical expressions. The present paper is focused on the characterization of the effect of non-uniformities in the reverse link of a WCDMA system. Thus, the major difference with respect to [1]-[2] lays on the fact that in [1] and [2] no services mix is considered, and so, only traffic spatial distributions are analysed. Furthermore, only a small number of traffic spatial distributions are analysed in [1] and [2], whereas in the paper presented herein general expressions are obtained.

Other approaches presented in the literature also cope with techniques to mitigate the effects caused by non-uniformities. RRM strategies have become one of the targets [3], specifically Call Admission Control, on which many studies have been carried out. In [4] and [5] different algorithms are presented and simulated, achieving positive results in maximising the capacity while minimising parameters such as blocking probability. Finally, pilot power management has also emerged as a solution to balance the load among base stations in non-homogeneous scenarios. For instance in [6]-[9] different algorithms are proposed, all of them focused on forward link. In this respect, the present paper may also provide inspiration for further development of these techniques, as long as the analytical approach allows gaining insight into the general problem.

With all the above, this paper focuses in modelling traffic non-homogeneities from an analytical perspective, so that the key issues affecting the problem can be extracted. The final objective is to propose an analytical model able to compute the maximum capacity (i.e. maximum uplink load factor) that can be supported in the uplink of a WCDMA cell under non-homogeneous spatial traffic distribution and multiple services. This maximum load factor value can then be used as an input to dynamic RRM strategies like e.g. admission or load control. Capacity will be defined for specific outage requirements. The remainder of the paper is organized as follows: the problem formulation is presented in section II. Section III proposes a model for computing the transmitted power distribution in non-uniformly distributed scenarios, focusing mainly on expressions for transmitted power. The outage probability is also derived in section III. Finally, section IV presents results

and section V summarizes conclusions.

## II. PROBLEM FORMULATION

The considered scenario is an isolated WCDMA cell with radius  $R$  (m). This scenario is composed of  $N$  overlapped layers ( $L_i$ , with  $0 \leq i \leq N-1$ ) in which traffic and services are defined. All layers are circular shaped with a radius  $r_i$  (m) and whose centre is placed  $D_i$  (m) from the cell site. In particular, layer  $L_0$  matches up with the cell area and so,  $D_0=0$  and  $r_0=R$  (the cell site is set as the coordinates origin). The scenario layout is displayed in Figure 1.

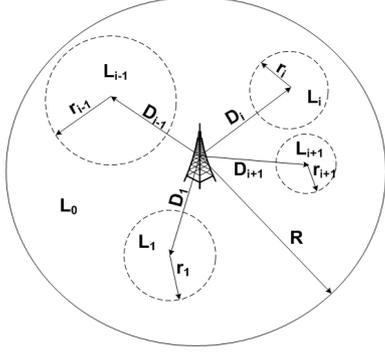


Figure 1. Scenario layout.

Let denote  $T_T$  as the overall number of users within the cell.  $T_T$  is distributed among the  $N$  layers and the proportion of users belonging to layer  $L_i$  is given by:

$$\alpha_i = \frac{T_i}{\sum_{j=0}^{N-1} T_j} = \frac{T_i}{T_T} \quad (1)$$

$T_i$  being the number of users within layer  $L_i$ . On the other hand,  $K$  possible services ( $0 \leq n \leq K-1$ ) are identified.  $\rho_{i,n}$  denotes the proportion of users with the  $n$ -th service in layer  $L_i$ . The traffic source is not continuously transmitting packets within a session and some activity periods alternate with inactivity periods (e.g. the reading time during a WWW download). Then, the activity factor ( $\varepsilon_n$ ) is defined as proportion of time in which a user is transmitting (taking into account session and intersession time). Each service is characterized by an activity factor.

Focusing now on the activity periods, in which a certain user is transmitting data through the air interface, there exist several TF (Transport Formats) for each service to transmit the data flow [11]. Each transport format is characterized essentially by a transmission bit rate, a channel code and a required  $(E_b/N_0)$ . The set of TFs is denoted as TFS (Transport Format Set). The set of possible bit rates for the  $n$ -th service are then:  $R_{b_{nj}}$  ( $0 \leq j \leq TFCS_n-1$ ) and the corresponding  $(E_b/N_0)$ :  $(E_b/N_0)_{nj}$  with  $0 \leq j \leq TFCS_n-1$ .  $p_{n,j}$  is defined as the probability of using the  $j$ -th TF of the  $n$ -th service, which depends on the

specific MAC algorithm that executes the Transport Format selection in the uplink [3].

In the following sections an analytical model of the reverse link of a multi-rate/multi-service WCDMA based system is developed. The main target of this work is to obtain a model to study the impact of non-uniformities on the performance of the system. The QoS (Quality of Service) parameter under study is the outage probability, defined as the probability that the measured  $E_b/N_0$  is below the target. Notice that outage is tightly coupled with transmitted power and so the study of the transmitted power becomes the key issue.

## III. ANALYTICAL MODEL

### III.A. Transmitted power distribution

In WCDMA based systems the capacity is highly dependant on the interference existing in the air interface. The main goal of this section is to find out the expression of the required transmitted power probability density function (pdf) to derive the system capacity. In the uplink case, the required transmitted power (in logarithmic units) is given by [3]:

$$P(\text{dBm}) = Z(\text{dB}) + 10 \log \left( \frac{P_N}{1-\eta} \right) - 10 \log \left( \frac{W}{\left( \frac{E_b}{N_0} \right) R_b} + 1 \right) \quad (2)$$

where  $W$  is the total bandwidth after spreading,  $P_N$  is the thermal noise power,  $Z$  is the path loss plus a shadowing component and  $\eta$  stands for the uplink load factor. For a given load factor the required transmitted power becomes a function of path loss,  $(E_b/N_0)$  and  $R_b$ . Thus, the required transmitted power ( $P$ ) probability density function may be worked out by calculating the pdf of the path loss ( $Z$ ), depending on traffic spatial distribution, and of the product  $(E_b/N_0)R_b$ , depending on service characterisation.

Let consider the problem formulated in section II. Propagation is characterised by a path loss dependant on the distance plus a lognormal shadowing component (assuming that closed-loop power control cancels all fast fading effects). The path loss at distance  $d$  (m) from the transmitter in logarithmic units,  $Y(\text{dB})$ , is given by [12]:

$$Y(\text{dB}) = Y_0 + \zeta \log(d) \quad (3)$$

Traffic spatial distribution determines the path loss distribution and in turn, determines the transmitted power distribution. Focusing on a generic layer  $L_i$  (characterized by its radius  $r_i$  and the distance  $D_i$  from the cell site to its centre) the path loss probability density function, denoted as  $f_Y^i(y)$ , is given by [10]:

$$\begin{aligned} & - \text{If } D_i \geq r_i: \\ & f_Y^i(y) = \frac{A\beta}{2\pi r_i^2} e^{\beta y} \left[ \pi - 2 \arcsin \left( \frac{D_i^2 - r_i^2 + A e^{\beta y}}{2D_i \sqrt{A e^{\beta y}}} \right) \right] \end{aligned} \quad (4)$$

for  $Y_0 + \zeta \log(D_i - r_i) \leq y \leq Y_0 + \zeta \log(D_i + r_i)$

– If  $D_i < r_i$ :

$$f_Y^i(y) = \frac{A\beta}{r_i^2} e^{\beta y} \quad (5)$$

for  $-\infty \leq y \leq Y_0 + \zeta \log(r_i - D_i)$

$$f_Y^i(y) = \frac{A\beta}{2\pi r_i^2} e^{\beta y} \left[ \pi - 2 \arcsin \left( \frac{D_i^2 - r_i^2 + Ae^{\beta y}}{2D_i \sqrt{Ae^{\beta y}}} \right) \right] \quad (6)$$

for  $Y_0 + \zeta \log(r_i - D_i) < y \leq Y_0 + \zeta \log(D_i + r_i)$

$$\text{where } A = 10^{-\frac{2L_{p0}}{\zeta}} \text{ and } \beta = \frac{2 \ln(10)}{\zeta}$$

Adding the effects of lognormal shadowing (S), the total propagation loss ( $Z=Y+S$ ) probability density function is the result of convolutioning (4) and a gaussian function with null mean and  $\sigma^2$  variance, so that the resulting probability density function can be expressed as:

$$f_Z^i(z) = f_Y^i(z) * \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{z^2}{2\sigma^2}} \quad (7)$$

Finally the overall path loss density function is obtained by summing each pdf weighted according to the traffic fraction ( $\alpha_i$ ). In particular, when  $N$  layers are considered (from 0 to  $N-1$ ) the overall path loss density function is given by:

$$f_Z(z) = \sum_{i=0}^{N-1} \alpha_i f_Z^i(z) \quad (8)$$

It may be observed from (2) that the required transmitted power is dependant on the product  $(E_b/N_0)R_b$ . The total path loss density function derived so far takes into account the total number of users in the scenario. In the case of WCDMA based systems only transmitting users (i.e. during activity periods) contribute to an increase of the interference. Taking this fact into account, the influence of each user on the total interference depends on parameters such as the activity factor ( $\epsilon_n$ ), the probability of selecting the  $j$ -th TF of the  $n$ -th service ( $p_{n,j}$ ) and the distribution of services within the layers ( $\rho_{i,n}$ ). Let define:

$$\Phi = 10 \log \left( \frac{P_N}{(1-\eta) \left( \frac{W}{\left( \frac{E_b}{N_0} \right) R_b} + 1 \right)} \right) \quad (9)$$

Since the selection of each TF for a specific service is a random variable, the probability function of  $\Phi$  is given by:

$$P_\Phi(\Phi = \phi_{n,j}) = P_\Phi(\phi_{n,j}) = \frac{\epsilon_n \alpha_i \rho_{i,n} p_{n,j}}{\sum_{s=0}^{K-1} \sum_{q=0}^{N-1} \alpha_q \epsilon_s \rho_{q,s}} \quad (10)$$

The discrete probability space in which (10) is defined is  $\Omega_\Phi = \{\phi_{0,0}, \phi_{0,1}, \dots, \phi_{N-1, TFCS_{N-1}-1}\}$ , where:

$$\phi_{n,j} = 10 \log \left( \frac{P_N}{(1-\eta) \left( \frac{W}{\left( \frac{E_b}{N_0} \right)_{n,j} \cdot R_{b_{n,j}}} + 1 \right)} \right) \quad (11)$$

for  $j=0, \dots, TFCS_n - 1$ .

Finally, and for a given load factor, the required transmitted power density function is obtained by convolutioning  $Z$  and  $\Phi$  probability density functions:

$$f_P(P) = f_Z(P) * f_\Phi(P) \quad (12)$$

$$f_P(P) = \frac{\sum_{n=0}^{K-1} \sum_{j=0}^{TFCS_n-1} \sum_{i=0}^{N-1} \alpha_i \epsilon_n \rho_{i,n} p_{n,j} f_Z^i(P - \phi_{n,j})}{\sum_{s=0}^{K-1} \sum_{q=0}^{N-1} \epsilon_s \alpha_q \rho_{q,s}} \quad (13)$$

### III.B. QoS evaluation

This section extracts from the previous model the QoS performance in terms of outage probability, which is defined as the probability of having a  $(E_b/N_0)$  below the target  $(E_b/N_0)_T$ . Outage occurs whenever the required transmit power level  $P$  is above the maximum available power at the terminal  $P_{Tmax}$ . Therefore the outage may be expressed as:

$$Outage = \text{prob} \left( \left( \frac{E_b}{N_0} \right) < \left( \frac{E_b}{N_0} \right)_T \right) = \text{prob}(P < P_{Tmax}) \quad (14)$$

For a given load factor, the outage probability expression is as follows:

$$Outage_\eta = \frac{\sum_{n=0}^{K-1} \sum_{j=0}^{TFCS_n-1} \sum_{i=0}^{N-1} \epsilon_n \alpha_i \rho_{i,n} p_{n,j} \int_{P_{Tmax}}^{\infty} f_Z^i(P - \phi_{n,j}) dP}{\sum_{s=0}^{K-1} \sum_{q=0}^{N-1} \epsilon_s \alpha_q \rho_{q,s}} \quad (15)$$

It is worth noting that all expressions developed so far have been obtained by considering circular layers. However, expressions and process followed are also applicable to any other shape if path loss density functions are known. It is also

remarkable that, for instance, it is possible to follow the same process if a measurement campaign is carried out and there is a previous knowledge of the area that is to be analysed in terms of path loss distribution.

#### IV. RESULTS

This section provides some sample results in order to illustrate the capabilities of the proposed model in a given scenario. In particular, the scenario is composed of two traffic layers ( $L_0$  and  $L_1$ ) and two services (service 0 and service 1). Scenario and services parameters are detailed in Table 1 and Table 2.

Service 0 could represent a conversational CBR service that generates traffic at 64 kbps. On the other hand, service 1 could represent an interactive service in which four different transmission bit rates are allowed. Notice that  $R_{b_{1,3}}$  is higher than 64 kbps whereas  $R_{b_{1,0}}$  is much lower than 64 kbps. This makes the selection of a transmission bit rate a key issue in terms of the generated interference and so in terms of QoS parameters such as outage probability. In turn, Table 3 presents the distribution of users among layers, with three different situations, denoted as  $S_0$ ,  $S_1$  and  $S_2$ . In the first case ( $S_0$ ) all users with service 0 are scattered within layer  $L_0$  whereas all users with service 1 remain within layer  $L_1$ . In case  $S_1$  there is the same number of users with service 0 and service 1 in both layers (i.e. there is no service non-uniformity but traffic spatial non-uniformity). Finally, in case  $S_2$  all users with service 0 are scattered in  $L_1$  and users with service 1 in  $L_0$ .

Table 1. Services' parameters.

Parameter	Service 0	Service 1
$\epsilon_n$	0.2	0.08
TFCS <sub>n</sub>	1	4
$R_{b_{n,0}}$	64 kbps	12.2 kbps
$(E_b/N_0)_{n,0}$	4 dB	2.5 dB
$R_{b_{n,1}}$	N/A	32 kbps
$(E_b/N_0)_{n,1}$	N/A	2.5 dB
$R_{b_{n,2}}$	N/A	64 kbps
$(E_b/N_0)_{n,2}$	N/A	2.5 dB
$R_{b_{n,3}}$	N/A	128 kbps
$(E_b/N_0)_{n,3}$	N/A	2.5 dB

Table 2. Scenario parameters.

Parameter	Value
$r_0$	1000m
$D_0$	0m
$\alpha_0$	0.5
$r_1$	50m
$D_1$	150m
$\alpha_1$	0.5

Table 3. Services distribution.

$\rho_{i,n}$	$S_0$	$S_1$	$S_2$
$\rho_{0,0}$	1.0	0.5	0.0
$\rho_{0,1}$	0.0	0.5	1.0
$\rho_{1,0}$	0.0	0.5	1.0
$\rho_{1,1}$	1.0	0.5	0.0

The considered scenario models a urban environment where specific areas present traffic spatial and/or service non-uniformities (e.g. bus stations). Service 1 has a TFCS>1 and

so, there is a probability associated to each of the possible TFs. These probabilities depend on the user equipment MAC algorithms for TF selection [3]. As these MAC algorithms are not the purpose of this study, two different sets of TF selection probabilities are considered and assumed to be the result of applying two MAC algorithms labelled as  $MAC_0$  and  $MAC_1$ .  $MAC_0$  and  $MAC_1$  probabilities are detailed in Table 4. Whereas  $MAC_1$  algorithm tends to select low bit transmission rates,  $MAC_0$  selects the highest bit transmission rate, thus representing two different QoS profiles.

Table 4. Service 1 TF selection probabilities.

	$MAC_0$	$MAC_1$
$p_{1,0}$	0.0	0.5
$p_{1,1}$	0.0	0.5
$p_{1,2}$	0.0	0.0
$P_{1,3}$	1.0	0.0

Let consider the  $MAC_0$  algorithm. Figure 2 displays the required transmitted power probability density function with  $\eta=0.8$ . In all cases ( $S_0$ ,  $S_1$ ,  $S_2$ ) two peaks can be observed. Each peak is associated to one of the layers (i.e. the one appearing at low power values is associated to  $L_1$  and the one appearing at high power values to  $L_0$ ). It is worth noting that service 0 has an activity factor  $\epsilon_0=0.2$  and service 1  $\epsilon_1=0.08$ . When different services with different activity factors ( $\epsilon_n$ ) are mixed, those services with high  $\epsilon_n$  will have a greater impact on the required transmitted power pdf. For instance, if the same number of users belonging to service 0 and service 1 were spread all over the cell, the number of simultaneous users belonging to service 0 would be 2.5 ( $\epsilon_0/\epsilon_1$ ) times bigger than the number of users belonging to service 1. Therefore, the probability of transmitting high power levels (associated to users in layer  $L_0$ ) is higher in  $S_0$  (all users belonging to service 0 are within layer  $L_0$ ) than in the others. On the other hand, when all users with service 0 are located in layer  $L_1$  (case  $S_2$ ), low transmitted power levels are more likely to occur. Finally, case  $S_1$  presents a more balanced situation between users in each layer because, although users with service 0 have a bigger impact on transmitted power, the proportion of users with each service is maintained equal in both layers.

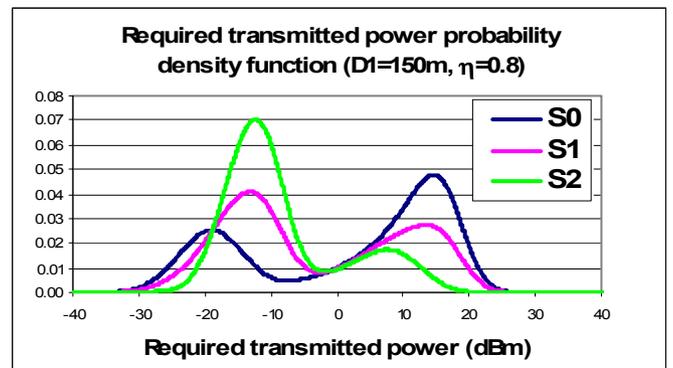


Figure 2. Required transmitted power probability density function.

The above explanation can be generalised to any load factor level. However, the higher the load factor is, the higher the required power level will be, thus increasing the outage. This effect is shown in Figure 3, which plots the performance of the system in terms of outage as a function of load factor.

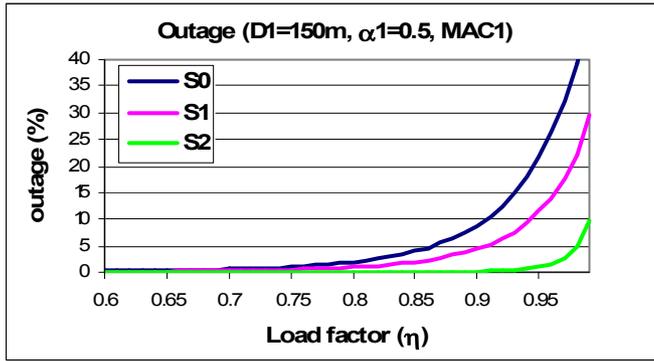


Figure 3. Outage for different users distributions.

The capacity of the system is determined by QoS (Quality of Service) parameters such as outage probability. If a maximum outage probability threshold is set ( $\text{Outage}_{\text{Threshold}}$ ), it is possible to determine the maximum load factor level ( $\eta_{\text{max}}$ ) that corresponds to this outage threshold. This maximum load factor level would be the input to the different uplink RRM algorithm like e.g. admission or load control. The impact of the two MAC algorithm and their associated TF probabilities is analysed in Figure 4. The outage threshold is set to 0.5% in  $S_0$  when  $\alpha_1=0.5$ . Notice that differences arise for high  $D_1$  values. In fact, results obtained with different MAC strategies are more significant as differences in used  $(E_b/N_0)_{\text{Rb}}$  grow. Figure 4 plots a comparison between the two algorithms detailed in Table 4 as a function of  $D_1$ . In this case the capacity is reduced when high transmission bit rates are more likely to be selected ( $\text{MAC}_0$ ). The capacity in terms of load factor is maintained for the whole range of  $D_1$  with  $\text{MAC}_1$  because selected transmission bit rates are low and do not imply an increase of the outage even for high  $D_1$ . When  $\text{MAC}_0$  is used, the selection of high transmission bit rates cause an increase on outage and so, the capacity is reduced.

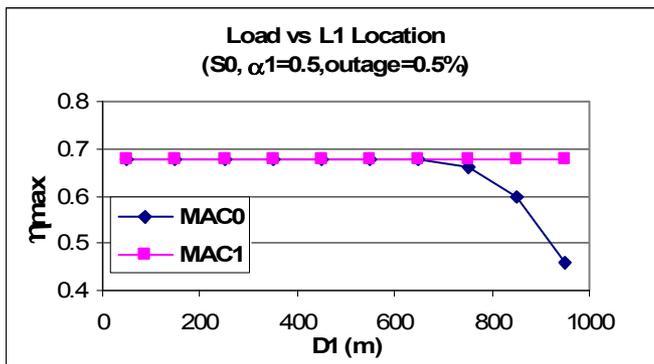


Figure 4. Load factor corresponding to  $\text{Outage}_{\text{Threshold}}=0.5\%$  for  $\text{MAC}_0$  and  $\text{MAC}_1$ .

## V. CONCLUSIONS

An analytical model has been proposed to evaluate the maximum allowable uplink load factor in a multi-service scenario WCDMA scenario with non-uniform traffic spatial distributions. Outage probability has been characterized for a circular cell with circular non-uniformities or hotspots, though the description of the process may be also applied to any known scenario by properly replacing the path loss probability density functions. Therefore, the proposed model allows a detailed study of the impact caused by the mix of different services in a multi-hotspot scenario.

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