Evaluation of Multi-service CDMA Networks with Soft Blocking

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Abstract

This paper presents an approach for calculating the capacity of multi-service CDMA networks with soft blocking using general holding time insensitive traffic models. The system is modelled as a multi-rate traffic flow model with state dependent blocking probabilities which have to fulfil specific requirements for maintaining reversibility of the model. Performance calculations are carried out by generalising Delbrouck's algorithm. An example for solving a realistic case is given.

Keywords: CDMA, soft blocking, Delbrouck's algorithm

1 Introduction

Universal Mobile Telecommunication System (UMTS) networks, being new entrants on the market, are trying to prove their existence and secure a position in the future. One of the innovations UMTS brings is multi-band Wide-Band Code Division Multiple Access (WCDMA), which allows many users to transmit simultaneously within the same frequency band. Novelty in WCDMA compared with GSM networks systems is that single-user transmission in the system to all other users located around the air-interface is noise. Every time a new call is accepted, the signal-to-noise ratios for all other users are decreased. Because of that, WCDMA systems have no hard limits on call capacity. In order to preserve the quality of already accepted calls, a new call should not be accepted by the system if this call increases the noise for any other existing call above the tolerable level. In (Staehle & Mäder [7]) the same problem is dealt with.

This paper presents a powerful and flexible model for evaluation of blocking probabilities of WCDMA system and related teletraffic parameters as traffic, call and time congestion. At the end, the paper gives an example of how to use the described model and algorithms.

The technique presented in the paper is based on the classical recurrence Erlang-B formula, further developed by Fortet and Grandjean (otherwise known as Kaufman and Roberts' algorithm) and Delbrouck. We generalise it to include global-state-dependent blocking probabilities.

In section 2 we review the basic principles of calculating the capacity of WCDMA for services with different bandwidth and Quality-of-Service (QoS) requirements. Section 3 presents a new compact recursion scheme based on Delbrouck's algorithm. In section 4 we introduce state dependent blocking probabilities as they appear in WCDMA. New results on conditions for product-form and reversibility are presented, and the above algorithm is generalised to global-state-dependent blocking probabilities. A realistic large scale case is presented in section 5, and conclusions are given in section 6.

2 WCDMA Capacity

WCDMA networks are designed to provide multi-rate services with diverse Quality-of-Service (QoS) parameters as different speed and bit error rates. In the following we consider a single UMTS cell for capacity analysis. Influence from neighbour cells is modelled by the noise, which is expressed by neighbour cell interference ratio i introduced below.

The usual way to describe WCDMA capacity is through signal and noise power levels and their ratio. Such modelling comes very close to physical network layer. However, for teletraffic calculations, it is preferable to convert all power levels and decibels into channels, offered traffic and blocking probabilities. Furthermore, only the up-link traffic direction (from mobile station towards the base station) will be considered. The down-link can be modelled in similar way. For that we need to express UMTS service definition by bandwidth resources needed from the particular traffic channel by the considered service.

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The relevant WCDMA cell capacity defining parameters are the following [4]:

- WCDMA chip rate, $W = 3.84$ Mcps.
- Noise-rise is defined as the ratio of the total received wide-band power to the noise power. It is functionally related to the cell up-link utilisation factor η_{UL} ([4] formula 8.9: *Noise rise* $= 1/(1-\eta_{\text{UL}})$). The value of 3 dB noise-rise corresponds to $\eta_{\text{UL}} = 50\%$ utilisation.
- Neighbour cell interference ratio i:

  $$i = \frac{\textit{other cell interference}}{\textit{own cell interference}}$$

  Interference ratio depends on cell environment, type of antenna used, and other factors. Common assumed values are 0.55 or 0.65. This makes cell capacity reduce by factor $1/(1+i)$. In this paper we include other cell interference by state dependent blocking probabilities b_x, discussed further.

Service classes in UMTS are described by following three parameters:

- Service bit-rate R_j;
- Signal energy per bit divided by noise spectral density level E_b/N_0 that is required to provide predefined QoS;
- Activity factor ν_j. For data services it equals 1, for voice 0.67 (50% voice activity plus overhead).

Let N denote the total number of active calls (or users) in the cell for all services. The mathematical relation between above entities is ([4] formula 8.12):

$$\eta_{\text{UL}} = \sum_{j=1}^{N} \frac{1}{1 + \frac{W}{\left(\frac{E_b}{N_0}\right)_j R_j \nu_j}} . \tag{1}$$

Let us denote the service-related entities product by κ_j:

$$\kappa_j = \left(\frac{E_b}{N_0}\right)_j R_j\, \nu_j\,. \tag{2}$$

Then the maximum number of channels of service j in one cell is:

$$N_{max,j} = \eta_{\text{UL}} \left(1 + \frac{W}{\kappa_j}\right). \tag{3}$$

Let us denote by $R_{s,j}$ the spread bit rate of service j, which is the proportion of W utilised by one connection of service R_j (the chip rate of the connection):

$$R_{s,j} = \frac{W}{N_{max,j}} = \frac{1}{\eta_{\text{UL}}} \left(\kappa_j - \frac{\kappa_j^2}{\kappa_j + W}\right). \tag{4}$$

The formula above provides the technique to obtain unified measure unit for calculating traffic in multi-service and multi-QoS WCDMA systems. An example of calculations using above formulæ is shown in the Table 1.

In the following we need to specify the total capacity and bandwidth requirement by a common bandwidth unit which we may call a channel. The higher the required accuracy, the smaller is the unit we have to choose. As an approximation we may choose the unit-channel to be equal to 13.5 kcps, and then approximate the bandwidth of the above services by 2, 4, 3, 5, 10, 16, 32 channels, respectively. The cell capacity is then $3840/13.5 = 284$ channels.

3 Algorithms for traffic performance

We may evaluate the above model by using teletraffic models. All models in the following are insensitive to the service time distribution and thus very robust for applications. In case of Poisson arrival processes the algorithms become very simple, and we find the value of state probability $q(x)$ relative to state $q(0) = 1$ by *Fortet & Grandjean's algorithm* (Fortet & Grandjean, 1964 [2]):

$$q(x) = \sum_{i=1}^{N} \frac{d_i\, A_i}{x} \cdot q(x - d_i)\,, \qquad q(0) = 1\,. \tag{5}$$

The state of the system x is the number of busy channels. For service i the offered traffic (in connections) is A_i, and each connection need d_i channels. This algorithm is usually called Kaufman & Roberts' algorithm, as it was re-discovered by these authors in 1981, but is was originally published in 1964 (Fortet & Grandjean [2]). The same model with *BPP*-traffic (BPP = Binomial & Poisson & Pascal) and without class limitation has been dealt with by several authors. Delbrouck's algorithm (Delbrouck, 1983 [1]) is the first and most general of these:

$$\begin{aligned} q(x) &= \frac{1}{x} \sum_{i=1}^{N} \left\{\frac{d_i\, A_i}{Z_i}\right\} \sum_{j=1}^{\lfloor x/d_i \rfloor} \left\{\frac{Z_i - 1}{Z_i}\right\}^{j-1} \\ &\quad \cdot\ q(x - j \cdot d_i)\,, \qquad x = 1, 2, \ldots, n \qquad (6) \\ q(0) &= 1\,, \end{aligned}$$

where $\lfloor x/d_i \rfloor$ denote the integer part of x/d_i. In this formula the traffic is more general. The peakedness Z characterises the arrival process [5]. For $Z = 1$ we have a Poisson arrival process, whereas $Z = 2$ is a more bursty Pascal arrival process. For $Z < 1$ we have a finite number of users (Binomial case) and more smooth traffic.

The relative state probabilities $q(x)$ are nor-

j	Service	R_j[kbps]	ν_j	$\left(\frac{E_b}{N_0}\right)_j$[dB]	$\left(\frac{E_b}{N_0}\right)_j$	κ_j	$N_{max,j}$	$R_{s,j}$[kcps]
1	Voice	7.95	0.67	4	2.51	13.38	144.0	27
2	Voice/moving	7.95	0.67	7	5.01	26.70	72.4	53
3	Voice	12.2	0.67	4	2.51	20.53	94.0	41
4	Data	16	1	3	2.00	31.92	60.6	63
5	Data	32	1	3	2.00	63.85	30.6	126
6	Data	64	1	2	1.58	101.43	19.4	198
7	Data	144	1	1.5	1.41	203.41	9.9	386

Table 1: *Capacity of a WCDMA cell. Assumptions for calculations for cell parameters:* η_{UL} *= 0.5 and* W *= 3840 kcps.*

malised to obtain the absolute state probabilities:

$$p(x) = \frac{q(x)}{Q_n}\,, \; Q_n = \sum_{i=0}^{n} q(i)\,, \; x = 0, 1, \ldots, n \qquad (7)$$

We may rewrite Delbrouck's algorithm as follows by observing that the inner summation in (6) is a geometric weighting of previous state probabilities [6]:

$$\begin{aligned}
\delta_i(x) &= \frac{d_i \cdot A_i}{Z_i}\, q(x-d_i) + \frac{Z_i - 1}{Z_i} \cdot \delta_i(x-d_i)\,, \\
\delta_i(x) &= 0 \quad \text{whenever} \quad x < d_i\,, \\
q(x) &= \frac{1}{x}\sum_{i=1}^{N} \delta_i(x)\,, \quad x = 1, 2, \ldots, n\,, \\
q(0) &= 1\,, \quad q(x) = 0 \quad \text{whenever} \quad x < 0\,.
\end{aligned}$$

The algorithm is explained as follows. When the state is increased from $x - d_i$ to x, we get an extra term in the inner sum of (6) which is the first term in (8). All previous terms are multiplied by an additional factor $\frac{Z_i - 1}{Z_i}$ and yield the second term in (8). For Poisson arrival processes we have $Z = 1$. This modified algorithm only requires a limited number of previous state probabilities. Therefore, we may normalise the state probabilities after each step in the iteration to avoid numerical problems as described in [5]. In each step we have to normalise not only $q(x)$, but also all $\delta_i(j)$, $i = 1, \ldots N$, $j = x, x-1, \ldots, x - d_i$.

4 State-dependent blocking

In CDMA the capacity limiting factor is the power transmitted by user terminals and antennas. The total power is made up of contributions from own cell, other cells, and background noise. The contribution from other cells is typically around 35–40 % (with $i = 0.55 - 0.65$), and it is often assumed to be an independent log-normal distributed random variable. Therefore, the blocking probability of a new connection in own cell is a random variable depending on the state of the system (own cell) and the bandwidth (noise-rise) of the new connection. In Fig. 1 we show a system with two multi-rate services. Let us denote the global state by x (e.g. $x = i + j$ in state (i,j)). If the state-dependent blocking probability b_x in state x for a single slot call is zero, then the state transition diagram is reversible and has product form. The reversibility is ensured when the flow among the four neighbour states is the same clockwise and counterclockwise (Kolmogorov cycles).

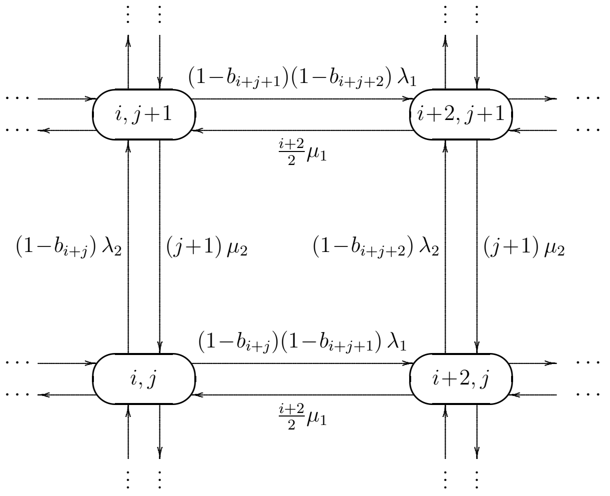

Figure 1: *State-transition diagram for state-dependent blocking probabilities for a multi-rate traffic. In this example the arrival processes are Poisson processes* (λ_1, λ_2)*, and the slot size is* $d_1 = 2$, $d_2 = 1$*, respectively.*

The passage factor is defined as $1 - b_x$. When b_x is greater than zero, then we may choose b_x so that the diagram is still reversible, but the product form will be lost. For a d–slot call we have to choose the passage factor in state x equals to number of channels occupied in the cell.

$$\begin{aligned}
1 - b_{x,d} &= \Pi_{j=x}^{x+d-1}(1 - b_j) \\
&= (1 - b_x)(1 - b_{x+1}) \ldots (1 - b_{x+d-1})
\end{aligned}$$

This corresponds to that a d-slot call chooses one single channel at a time (d times), and the call is only accepted if all d channels are successfully obtained. This is a quite natural requirement as we

Class	A	Z	d
1	30.00	2.00	2.00
2	15.00	1.00	4.00
5	6.00	0.40	10.00
6	3.75	0.25	16.00

Table 2: *Input parameters for the case considered. A is offered traffic, Z peakedness and d bandwidth requirement in channels. The total number of channels is 284.*

assume full accessibility, and it can be shown to be a necessary and sufficient condition for maintaining the reversibility of the process. If the process is not reversible, then we have to solve a very large set of linear equations to find the state probabilities, and only very small systems can be solved. The product form will be lost. As the blocking probability only depends on the global state and the QoS & bandwidth requirements (noise-rise) of the new connection, we may introduce the state-dependent blocking probability as follows. The procedure is as follows:

1. we first calculate the global state probabilities for a system without state dependent blocking (section 3),
2. then we modify these states by the state dependent blocking probabilities.

For example, Fortet & Grandjean's algorithm (6) will be modified in the following way:

$$q(x) = \sum_{i=1}^{N} \frac{d_i\, A_i}{x} \cdot q(x-d_i)(1-b_{x-d_i,d_i})\,, \qquad q(0)=1\,. \tag{8}$$

Other algorithms are modified in a similar simple way. We are thus able to obtain the exact global state probabilities for a system with global-state dependent blocking probabilities as they appear in CDMA systems, even if the system does not have a product-form.

5 Case study

We consider an example with 4 services from table 1 with the parameters shown in table 2. The offered traffic A is given in number of connections, and the bandwidth demand d in number of bandwidth units (channels). The maximum number of channels is 284. In addition to these parameters, the model and program also allows for minimum guaranteed allocation of capacity and maximum allowed capacity for each service and other features not included here.

For a system with full accessibility and 284 channels the performance measures are shown in table 3. We consider three congestion measures.

- The time congestion E is the proportion of time a service is blocked.
- The call congestion B is the proportion of call attempts which are blocked.
- The traffic congestion C is the proportion of offered traffic which is blocked, where we define the offered traffic as the traffic carried when the capacity is unlimited.

For Poisson arrival processes ($Z = 1$) we have the *PASTA*–property and the three measures are identical. In all other cases the traffic congestion is the most relevant. The carried traffic is measured in channels. We notice that the four services have almost the same performance because $Z \cdot d = 4$ is constant.

In table 4 the same model is considered with state dependent blocking. The state-dependent blocking probability is log-normally distributed, as presented in previous section.

We introduce log-normal random process X' of neighbour cell interference with parameters:

$$\begin{aligned} \mu &= \frac{i}{i+1} \cdot N \\ \sigma &= \mu \end{aligned} \tag{9}$$

N is our cell capacity of the cell in channels. The mean value of the interference process μ is equal to the average capacity lost in our cell because of the neighbour cell. σ is chosen to be equal to the μ as proposed by (Staehle & Mäder [7]).

Then b_x is expressed as the probability that the neighbour cell interference is greater than the available capacity in the current cell $(N - x)$:

$$\begin{aligned} b_x &= P(x' > N - x) \\ &= 1 - P(x' < N - x) \\ &= 1 - D(N - x) \end{aligned}$$

Here $D(x)$ is the cumulative distribution function of the log-normal distribution:

$$D(x) = 1/2\left(1 + erf\left(\frac{ln(x) - M}{S\sqrt{2}}\right)\right) \tag{10}$$

where M and S are corresponding parameters of normal distribution and are obtained from μ and σ^2 by the following calculations:

$$\begin{aligned} M &= \ln\left(\frac{\mu^2}{\sqrt{\mu^2+\sigma^2}}\right) \\ S^2 &= \ln\left(1 + \frac{\sigma^2}{\mu^2}\right) \end{aligned}$$

We choose the other cell interference factor $i = 0.55$ and the cell capacity $N = 284$ (channel rate - 13.5 kcps). Then the interference process mean value $\mu = 100.7$ and we assume multiplicative variance $\sigma^2 = 10140.495$.

Class	Time cong. E	Traffic cong. C	Call Cong. B	Carried Traffic
1	0.010133	0.022239	0.011245	58.665650
2	0.021220	0.021220	0.021220	58.726826
5	0.060565	0.018243	0.044394	58.905396
6	0.109536	0.015518	0.059312	59.068904
Total		0.019305		235.366777

Table 3: *Performance measures for the parameters given in table 2 and without state-dependent blocking.*

Class	Time cong. E	Traffic cong. C	Call Cong. B	Carried Traffic
1	0.262984	0.418228	0.264405	34.906318
2	0.458604	0.458604	0.458604	32.483784
5	0.789709	0.594068	0.785346	24.355907
6	0.920837	0.735190	0.917391	15.888620
Total		0.551522		107.634629

Table 4: *Performance measures for the parameters given in table 2 and with state-dependent blocking.*

6 Conclusions

The paper presents a new and innovative approach to evaluate CDMA systems. We first show a way to calculate R_s using a common unit and describing speed and QoS of WCDMA services in a particular cell. Then we discuss state-dependent blocking probabilities and show how they should be chosen to conform with reality and at the same time maintain reversibility of the process. Even if the product-form of the model is lost by introducing blocking, we are able to calculate the exact state probabilities by a two-step procedure first using the known algorithms and then modifying the result in a simple way. The general Delbrouck-algorithm is presented in a modified form only requiring a minimum of memory and maintaining full numerical accuracy. The model has been implemented in C++ language [3].

The model described is flexible and can be applied for different services and state dependent blocking probabilities for any system size.

References

[1] Delbrouck L.E.N.: *On the steady–state distribution in a service facility carrying mixtures of traffic with different peakedness factor and capacity requirements.* IEEE Transactions on Communications, Vol. COM–31 (1983) : 11, 1209–1211.

[2] Fortet R. & Grandjean Ch.: *Congestion in a loss system when some calls want several devices simultaneously.* Electrical Communications, Vol. 39 (1964) : 4, 513–526. Paper presented at ITC–4, Fourth International Teletraffic Congress, London. England, 15–21 July 1964.

[3] Ha, N.T.: *Bandwidth allocation for Internet.* Master thesis. COM, Technical University of Denmark, October 2003.

[4] Holma H. & Toskala A. (editors): *WCDMA for UMTS: Radio Access for Third Generation Mobile Communications*, 2nd Edition, 412 pp. Wiley, July 2002

[5] Iversen V.B.: *Teletraffic Engineering Handbook.* COM Center, Technical University of Denmark. 2002. 338 pp. To be published by ITU.

[6] Iversen V.B. & Stepanov S.N. & Kostrov V.O.: *The Derivation of a Stable Recursion for Multi–Service Models.* Proc. of International Conference on Next Generation Teletraffic and Wired/Wireless Advanced Networking, NEW2AN, pp. 254–265 St. Petersburg, Russia. February 2–6, 2004. 12 pp.

[7] Staehle, D. & Mäder, A.: *An analytic approximation of the uplink capacity in a UMTS network with heterogeneous traffic.* Proceedings of ITC 18, Berlin September 2003, pp. 81-91. Elsevier 2003.