Paper

QoS Equalization in a W-CDMA Cell Supporting Calls of Infinite or Finite Sources with Interference Cancelation

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Abstract—In this paper, a multirate loss model for the calculation of time and call congestion probabilities in a Wideband Code Division Multiple Access (W-CDMA) cell is considered. It utilizes the Bandwidth Reservation (BR) policy and supports calls generated by an infinite or finite number of users. The BR policy achieves QoS equalization by equalizing congestion probabilities among calls of different service-classes. In the proposed models a multiple access interference is considered, and the notion of local blocking, user's activity and interference cancelation. Although the analysis of the proposed models reveals that the steady state probabilities do not have a product form solution, the authors show that the calculation of time and call congestion probabilities can be based on approximate but recursive formulas, whose accuracy is verified through simulation and found to be quite satisfactory.

Keywords—bandwidth reservation, infinite/finite sources, recursive formula, time-call congestion probabilities, W-CDMA.

1. Introduction

Wideband Code Division Multiple Access (W-CDMA) networks support calls from different service-classes with heterogeneous Quality of Service (QoS) requirements. The existence of own-cell and other-cell interference in these networks, increases the complexity of the call-level analysis both in the uplink (UL) and downlink directions.

We study the UL direction of a W-CDMA cell that has fixed capacity and supports K service-classes whose calls are generated by an infinite and finite number of sources. In the first case, the call arrival process is the Poisson process while in the second case the call arrival process is a quasi-random process [1]. Calls of service-class k $(k = 1, \ldots, K)$ have a fixed bandwidth requirement and an exponentially distributed service time. According to the CDMA principle of W-CDMA networks a call is noise for all in-service calls. Therefore, a new call is accepted in the cell if its bandwidth requirement is available and the noise of all in-service calls remains below a tolerable level.

To take into account the interference increase caused by the acceptance of the new call, the notion of Local Blocking (LB) was adopted in analysis. The latter means that a new call can be blocked in any system state, if its acceptance results in the increase of noise of all in-service calls above a threshold.

We model a reference W-CDMA cell as a multirate teletraffic loss system, and aim at calculating Time and Call Congestion Probabilities (TC and CC probabilities, respectively) via recursive formulas [2]–[4]. In [2]–[4], the calculation of congestion probabilities is based on the classical Kaufman-Roberts recursive formula used in the Erlang Multirate Loss Model (EMLM). The Kaufman-Roberts formula determines, in an efficient way, the link occupancy distribution for a single link that accommodates, under the Complete Sharing (CS) policy, Poisson calls of K service-classes with different bandwidth requirements and generally distributed service time [5], [6]. In [2], an extension of the EMLM is proposed, based on the Delbrouck's model (where a Bernoulli/Poisson/Pascal call arrival process is considered) [7]. This model allows new calls to have different peakedness factors. In [3], new calls are generated by an infinite number of sources, i.e., calls follow a Poisson process. In [4], calls come from a finite number of sources, a rather realistic case since cells have limited coverage area. As far as the LB modeling is concerned, two approaches exist in the literature. The first ensures reversibility in the underlying Markov state transition diagram but is complex [2]. We adopt the second approach, proposed in [3], since it is simpler and more realistic for W-CDMA systems. The interested reader may resort to [4] for a comparison of these approaches.

In this paper, a research from [3] and [4] is extended by applying the Bandwidth Reservation (BR) policy to guarantee call-level QoS for each service-class. In particular, an equalization of TC or CC probabilities is achieved among different service-classes by reserving bandwidth in favor of service-classes whose calls have high bandwidth requirements. Applications of the BR policy in wired (e.g., [8]–[13]), wireless (e.g., [14]–[17]) and optical networks (e.g., [18],[19]) show the importance of the policy in teletraffic engineering. In addition, the authors study the effect of Interference Cancelation (IC) on congestion probabilities and provide recursive formulas for their calculation. Note that IC receivers reduce own-cell interference and thus decrease congestion [4].

This paper is organized as follows. In Section 2, the basic formulas in the UL of a W-CDMA cell are reviewed. In Section 3, random (Poisson) arrivals are considered and recursive formulas for the calculation of TC and CC probabilities under the BR policy are proposed. In Section 4, the case of quasi-random arrivals is considered. In Section 5, numerical results are presented and evaluated by simulation. The paper is concluded in Section 6.

2. Basic Formulas in the UL of a W-CDMA Cell

Consider the UL direction of a W-CDMA reference cell which is controlled by a Base Station (BS) and surrounded by other cells. This cell is modeled as a multirate loss system that supports K different service-classes. A service-class k $(k = 1,\ldots,K)$ call, when accepted in the system, alternates between transmission (active) and non-transmission (passive) periods. The ratio of "active" over "active + passive" periods is the activity factor of a service-class k call, v_k.

In the W-CDMA cell, a user "sees" the signals generated by other users as interference. Thus, the BS's capacity is limited by the own-cell interference, P_{own}, caused by the users of the reference cell and the other-cell interference, P_{other}, caused by the interference power received from users of the neighboring cells. Due to the stochastic nature of interference, we consider the interference limited capacity of the radio interface. Thermal noise is also considered, P_{noise}, which corresponds to the interference of an empty W-CDMA system. The values of P_{own} are reduced by the application of IC, whose efficiency, β, can be determined by [20]:

$$\beta = \frac{P_{\text{own}}^{\text{No IC}} - P_{\text{own}}}{P_{\text{own}}^{\text{No IC}}} \Rightarrow P_{\text{own}} = P_{\text{own}}^{\text{No IC}}(1-\beta), \qquad (1)$$

where $P_{\text{own}}^{\text{No IC}}$ is the own-cell interference without IC.

Let P_k be the total received power from a service-class k user. Then, the power control equation is [20]:

$$(E_b/N_0)_k = \frac{G_k P_k}{(P_{\text{own}} - P_k)(1-\beta) + P_{\text{other}} + P_{\text{noise}}}, \qquad (2)$$

where $(E_b/N_0)_k$ is the signal energy per bit divided by the noise spectral density, $G_k = W/v_k R_k$ is the processing gain of service-class k in the UL with data rate R_k and W the chip rate of 3840 kcps. Based on Eq. (2), the values of P_k are given by:

$$P_k = (P_{\text{own}}(1-\beta) + P_{\text{other}} + P_{\text{noise}})/(1-\beta+G_k/(E_b/N_0)_k). \qquad (3)$$

Assuming that $P_{\text{own}} = P_k N_k$, where N_k is the maximum number of service-class k calls in the cell, we have [4]:

$$P_{\text{own}} = \frac{N_k(P_{\text{other}}+P_{\text{noise}})}{1-\beta-N_k(1-\beta)+G_k/(E_b/N_0)_k}. \qquad (4)$$

Consider now the Noise Rise (NR), defined as [21]:

$$NR = P_{total}/P_{noise} = (P_{own} + P_{other} + P_{noise})/P_{noise}, \qquad (5)$$

where $P_{\text{total}} = P_{\text{own}} + P_{\text{other}} + P_{\text{noise}}$ is the total received power at the BS.

The relation between the NR and the total UL cell load, η_{UL}, is given by [22]:

$$NR = 1/(1-\eta_{UL}), \qquad \eta_{UL} = (P_{\text{own}} + P_{\text{other}})/P_{\text{total}}. \qquad (6)$$

Based on Eqs. (4)–(6) it is proved that [4]:

$$N_k = \left[(1-\beta) + G_k/\left(E_b/N_0\right)_k\right] \frac{[\eta_{UL}(\delta+1)-\delta]}{[1-\beta(\eta_{UL}(\delta+1)-\delta)]}, \quad \delta \equiv P_{\text{other}}/P_{\text{noise}}. \qquad (7)$$

Based on Eq. (7), the spread data rate $R_{s,k}$ of service-class k, as a proportion of W is determined:

$$R_{s,k} = W/N_k. \qquad (8)$$

Now, we transform W and $R_{s,k}$ to the capacity C and the bandwidth b_k, of each service-class k, respectively. This is achieved by considering a basic bandwidth unit (*bbu*) as the greatest common divisor of the bandwidth of all service-classes, or as an arbitrarily chosen small value. So, $C = \lceil W/bbu \rceil$ and $b_k = \lceil R_{s,k}/bbu \rceil$ channels.

3. Congestion Probabilities Under the BR Policy – the Case of Random Arrivals

Consider a new service-class k call that arrives in the cell according to a Poisson process with mean arrival rate λ_k and requires b_k channels in order to be accepted in the system. Let j be the number of occupied cell's channels at the time of arrival, $j=0,1,\ldots,C$. Also, let t_k be the BR parameter that expresses the reserved channels to benefit calls of all service-classes other than service-class k. Due to the BR policy, the service-class k call is not allowed to enter the states $j=C-t_k+1,\ldots,C$. These states form the so-called reservation space of service-class k. So, after the acceptance of the call, $j \le C-t_k$, i.e., the available capacity upon the call arrival is $C-t_k-j$. Now two types of blocking states j are considered: hard blocking states due to bandwidth unavailability and soft (local) blocking states with a probability $0 < L_{j,k} < 1$ (LB states) due to the other-cell interference. The latter is approximated by an independent, lognormally distributed random variable, with parameters μ and σ [4]:

$$\mu = \frac{P_{\text{other}} + P_{\text{noise}}}{P_{\text{own}}+P_{\text{other}}+P_{\text{noise}}} C \Rightarrow \mu = \frac{i+i/\delta}{1+i+i/\delta} C, \quad \sigma = \mu, \qquad (9)$$

where $i = P_{\text{other}}/P_{\text{own}}$.

The LB probability (LBP) in state j, L_j, is the probability that the other-cell interference is greater than the available cell's capacity $(C-t_k-j)$ [4]:

$$L_j = 1-P\left(j' < C-t_k-j\right) = 1-CDF(C-t_k-j), \qquad (10)$$

where j' refers to the occupied channels due to the other cell interference and $CDF(x)$ is the cumulative distribution function of the lognormal distribution.

The values of $CDF(x)$ are given by:

$$CDF(x) = \frac{1}{2}\left(1 + erf\left(\frac{\ln(x) - M}{S\sqrt{2}}\right)\right), \quad (11)$$

where erf is the error function, while M and S refer to the parameters of the normal distribution:

$$M = \ln\left(\mu^2 \Big/ \sqrt{\mu^2 + \sigma^2}\right), \quad S = \sqrt{\ln\left(1 + \left(\sigma^2/\mu^2\right)\right)}. \quad (12)$$

The service-class k call is accepted in the cell if all b_k channels are assigned to the call simultaneously. Thus, it is assumed that P_{other} and LBP do not alter during this allocation process. We express the passage factor $1 - L_{j,b_k}$, i.e., the probability that the call is not blocked due to the other-cell interference as a function of j and b_k:

$$1 - L_{j,b_k} = 1 - L_{j+b_k+1} = CDF(C - t_k - j - b_k + 1). \quad (13)$$

Thus, the transition rate from $(j - b_k)$ to (j) equals $\left(1 - L_{j-b_k,b_k}\right)\lambda_k = \left(1 - L_{j-1}\right)\lambda_k$. Figure 1 presents an excerpt of the system's state transition diagram, which is depicted by a one-dimensional Markov chain. Note that μ_k is the mean service rate of service-class k calls, while $y_k(j)$ is the average number of service-class k calls in state j.

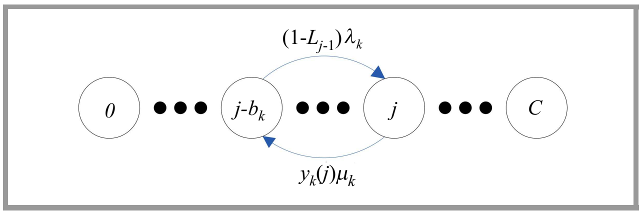

Fig. 1. State transition diagram for Poisson arriving service-class k calls with LB between states $j - b_k$ and j.

To calculate the un-normalized values of the system state probabilities, $q(j)$, the following approximate but recursive formula is proposed:

$$q_{\inf}(j) = \begin{cases} 1, & \text{for } j = 0 \\ \frac{1}{j}\sum\limits_{k=1}^{K} a_k D_k(j - b_k) q_{\inf}(j - b_k)(1 - L_{j-b_k,b_k}) & \text{for } j = 1, \ldots, C \\ 0, & \text{otherwise} \end{cases}, \quad (14)$$

$$D_k(j - b_k) = \begin{cases} b_k & \text{for } j \le C - t_k \\ 0 & \text{for } j > C - t_k \end{cases}, \quad (15)$$

where: $\alpha_k = \lambda_k/\mu_k$ is the offered traffic-load of service-class k calls (in erl), t_k is the BR parameter, while the values of $\left(1 - L_{j-b_k,b_k}\right)$ are determined by:

$$\left(1 - L_{j-b_k,b_k}\right) = 1 - L_{j-1} = CDF(C - t_k - j + 1). \quad (16)$$

Note that Eq. (15) facilitates the introduction of the BR policy in the model. The underlying assumption of Eq. (15) is that the population of service k calls, which require b_k channels while $t_k > 0$, is negligible inside the reservation space of service-class k, i.e., when $j = C - t_k + 1, \ldots, C$. In the case of the CS policy, Eq. (14) takes the form [3], [4]:

$$q_{\inf}(j) = \begin{cases} 1, & \text{for } j = 0 \\ \frac{1}{j}\sum\limits_{k=1}^{K} a_k b_k q_{\inf}(j - b_k)(1 - L_{j-b_k,b_k}), & \text{for } j = 1, \ldots, C \\ 0, & \text{otherwise} \end{cases}. \quad (17)$$

If we do not consider the existence of LB, then the classical Roberts' formula for the EMLM under the BR policy arises [8]:

$$q_{\inf}(j) = \begin{cases} 1, & \text{for } j = 0 \\ \frac{1}{j}\sum\limits_{k=1}^{K} a_k D_k(j - b_k) q_{\inf}(j - b_k), & \text{for } j = 1, \ldots, C \\ 0, & \text{otherwise} \end{cases}, \quad (18)$$

where the values of $D_k(j - b_k)$ are given by Eq. (15).

Having determined $q_{inf}(j)$'s according to Eq. (14), TC probabilities of service-class k, P_{b_k}, can be calculated as follows:

$$P_{b_k} = \sum_{j=0}^{C} G^{-1} L_{j,\, j+b_k} q_{\inf}(j), \quad (19)$$

where $G = \sum_{j=0}^{C} q_{\inf}(j)$ is the normalization constant and the values of $L_{j,\, j+b_k} = 1 - CDF(C - t_k - j - b_k + 1)$.

Note that TC probabilities refer to the proportion of time the system is congested, while CC probabilities refer to the proportion of arriving calls that find the system congested. TC and CC probabilities coincide in the case of Poisson arrivals due to the PASTA property [1].

4. Congestion Probabilities Under the BR Policy – the Case of Quasi-Random Arrivals

In the case of quasi-random arrivals, this part follows again the analysis of Section 3 up to Eq. (13). At this point, the transition rate from $(j - b_k)$ to (j), becomes: $\left(1 - L_{j-b_k,b_k}\right)(S_k - \overline{n_k}(j - b_k))\gamma_k = \left(1 - L_{j-1}\right)(S_k - \overline{n_k}(j - b_k))\gamma_k$, where S_k is the finite number of service-class k traffic sources, γ_k is the arrival rate from an idle source of service-class k and $\overline{n_k}(j)$ is the average number of service-class k

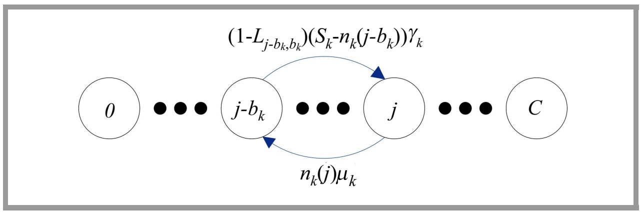

Fig. 2. State transition diagram for quasi-random arriving service-class k calls with LB between states $j - b_k$ and j.

calls in state j. Figure 2 shows the corresponding one-dimensional Markov chain.

To determine the un-normalized values of $q(j)$'s we propose the following recursive formula, for $j = 1, \ldots, C$:

$$q(j)=\frac{1}{j}\sum_{k=1}^{K}(S_k-n_k(j)+1)a_{k,\text{fin}}D_k(j-b_k)q(j-b_k)(1-L_{j-b_k,b_k}), \quad (20)$$

where: $q(0)$=1, $q(x)$=0 for $x < 0$, $a_{k,\text{fin}} = \gamma_k/\mu_k$ is the offered traffic-load per idle source of service-class k (in erl), $\overline{n_k}(j-b_k) = n_k(j)-1$, $n_k(j)$ refers to the number of in-service calls of service-class k in state j, while the values of $D_k(j-b_k)$ and $\left(1-L_{j-b_k,b_k}\right)$ are given by Eqs. (15) and (16), respectively.

In the case of the CS policy, Eq. (20) takes the form [4]:

$$q(j) = \frac{1}{j}\sum_{k=1}^{K}(S_k-n_k(j)+1)a_{k,fin}b_k q(j-b_k)(1-L_{j-b_k,b_k}), \quad (21)$$

Note that if $S_k \to \infty$ for $k = 1, \ldots, K$, and the total offered traffic-load remains constant, then the call arrival process is Poisson. In that case, Eqs. (20) and (21) become Eqs. (14) and (17), respectively.

The determination of $q(j)$'s in Eqs. (20) or (21) requires the values of $n_k(j)$ in each state j. These values are unknown and difficult to be determined. In other finite multirate loss models (e.g., [23]–[26]) there exist methods for the determination of $n_k(j)$ through an equivalent stochastic system, with the same traffic description parameters and exactly the same set of states. However, the state space determination of the equivalent system is complex, especially for large capacity systems that serve many service-classes. Thus, $n_k(j)$ is approximated, as the mean number of service-class k calls in state j, $y_k(j)$, when Poisson arrivals are considered, i.e., $n_k(j) \approx y_k(j)$ and consequently $n_k(j)-1 \approx y_k(j-b_k)$. Such approximations induce little error (e.g., [27]–[33]).

Based on the abovementioned approximation, Eqs. (20) and (21) take the form of (22) and (23), respectively:

$$q(j)=\frac{1}{j}\sum_{k=1}^{K}(S_k-y_k(j-b_k))a_{k,\text{fin}}D_k(j-b_k)q(j-b_k)(1-L_{j-b_k,b_k}), \quad (22)$$

$$q(j)=\frac{1}{j}\sum_{k=1}^{K}(S_k-y_k(j-b_k))a_{k,\text{fin}}b_k q(j-b_k)(1-L_{j-b_k,b_k}), \quad (23)$$

where the values of $y_k(j)$, for Poisson arrivals, are given by:

$$y_k(j) = a_k(1-L_{j-b_k,b_k})q_{\text{inf}}(j-b_k)/q_{\text{inf}}(j). \quad (24)$$

Having determined LBP by Eq. (16) and $q(j)$'s by Eq. (22) TC probabilities of service-class k calls is calculated, P_{b_k}, based on Eq. (19). Equation (19) can also be used for the determination of CC probabilities of service-class k, but $q(j)$'s should be calculated by Eq. (22) assuming $S_k - 1$ traffic sources.

5. Numerical Examples – Evaluation

The authors compare the analytical and simulation TC probabilities results obtained by the proposed models for different values of the IC efficiency β. For further comparison, the corresponding analytical results obtained in the case of the CS policy, for both Poisson and quasi-random arrivals [4] are also shown. Simulations are based on the SIMSCRIPT III language [34] and are mean values of 7 runs.

Consider a W-CDMA reference cell that accommodates quasi-random arriving calls of K=3 different service-classes. Accepted calls remain in the system for an exponentially distributed service time with mean value $\mu_1^{-1} = \mu_2^{-1} = \mu_3^{-1} = 1$. Table 1 presents the traffic characteristics of all service-classes. In addition, the following assumptions were made: $\eta_{UL} = 0.75$, $i = 0.35$, $\delta = 2$, $bbu = 13.5$ kcps, while the IC efficiency β takes the values 0.0 and 0.8. When $\beta = 0$, the bandwidth requirements and the corresponding BR parameters of all service-classes are: $b_1 = 4$, $b_2 = 7$, $b_3 = 64$ and $t_1 = 60$, $t_2 = 57$, $t_3 = 0$. The values of the BR parameters are chosen according to the rule: $b_1+t_1 = b_2+t_2 = b_3$, to achieve equalization of congestion probabilities. Similarly, when $\beta = 0.8$ then $b_1=4$, $b_2=5$, $b_3=54$ and $t_1=50$, $t_2=49$, $t_3=0$.

Table 1
Traffic parameters of all service-classes

Serv.-class k	R_k [kb/s]	v_k	$\left(\frac{E_b}{N_0}\right)_k$ [dB]	$\left(\frac{E_b}{N_0}\right)_k$	S_k	$a_{k,\text{fin}}$ [erl]	a_k [erl]
1	7.95	0.67	4.0	2.51	20	0.15	3.0
2	12.20	0.67	4.0	2.51	10	0.20	2.0
3	144.00	1.00	2.0	1.58	5	0.01	0.05

In the x-axis of Figs. 3–8 the offered traffic load of the 1st, 2nd and 3rd service-class increase in steps of 0.05, 0.10 and 0.002 erl, respectively. So, point 1 refers to: $(a_{1,\text{fin}}, a_{2,\text{fin}}, a_{3,\text{fin}} = (0.15, 0.20, 0.01)$ while point 6 to: $(a_{1,\text{fin}}, a_{2,\text{fin}}, a_{3,\text{fin}} = (0.40, 0.70, 0.02)$. Figures 3–4 present the analytical and simulation results of the 1st service-class for $\beta = 0$ and 0.8, respectively. Similarly, in Figs. 5–6 and 7–8, the corresponding results of the 2nd and 3rd service-class are presented, respectively. The proposed formulas for the calculation of the occupancy distribution and consequently TC probabilities in the case of the BR policy give quite accurate results in comparison with the simulation results. The increase of β results in the TC probabilities decrease, since the IC reduces the own-cell interference. The TC probabilities obtained by considering the CS policy fail to approximate the corresponding TC probabilities in the case of the BR policy. The application of the BR policy results in a slight decrease of the TC probabilities of the 3rd service-class compared to the increase of the TC probabilities of the other two service-classes. This is expected since the bandwidth per call requirement of the 3rd service-class is much higher (64 b.u.) than the requirements of the other service-classes (7 and 4 b.u.).

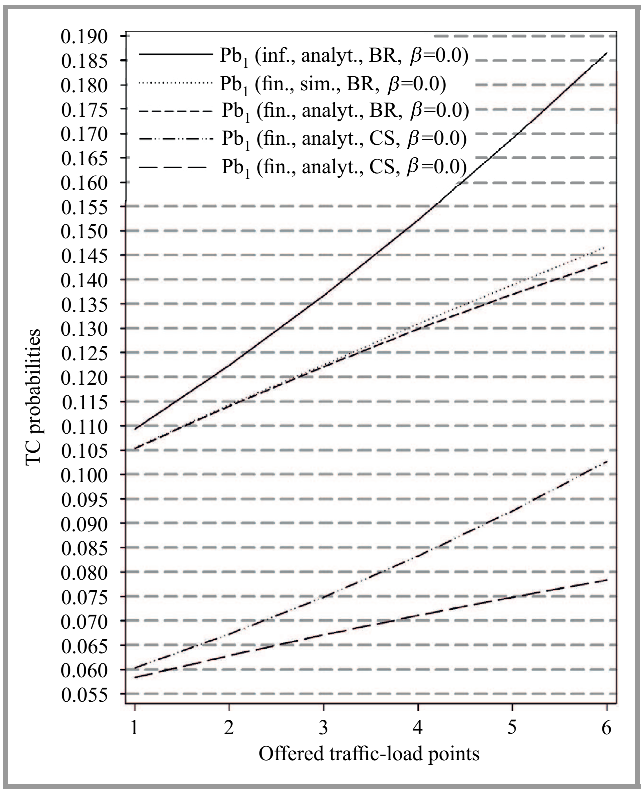

Fig. 3. TC probabilities – 1st service-class ($\beta = 0$).

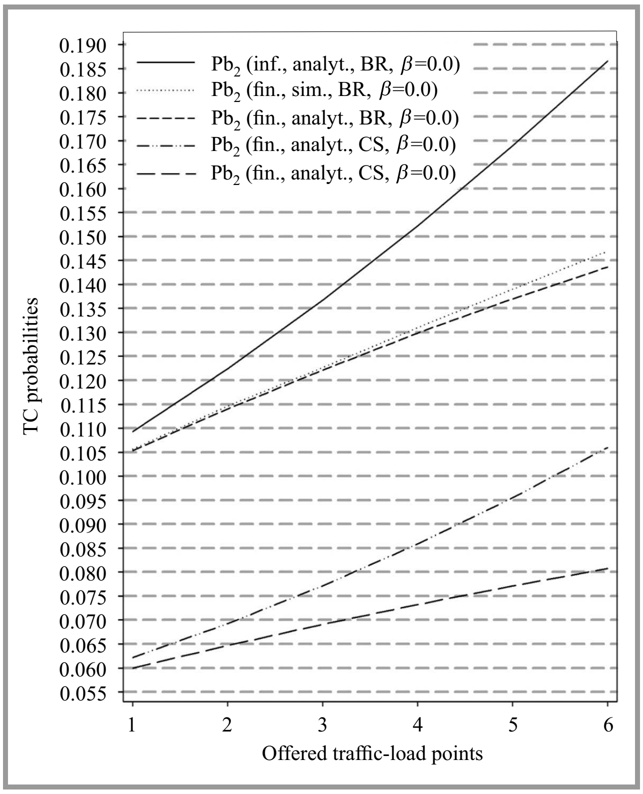

Fig. 5. TC probabilities – 2nd service-class ($\beta = 0$).

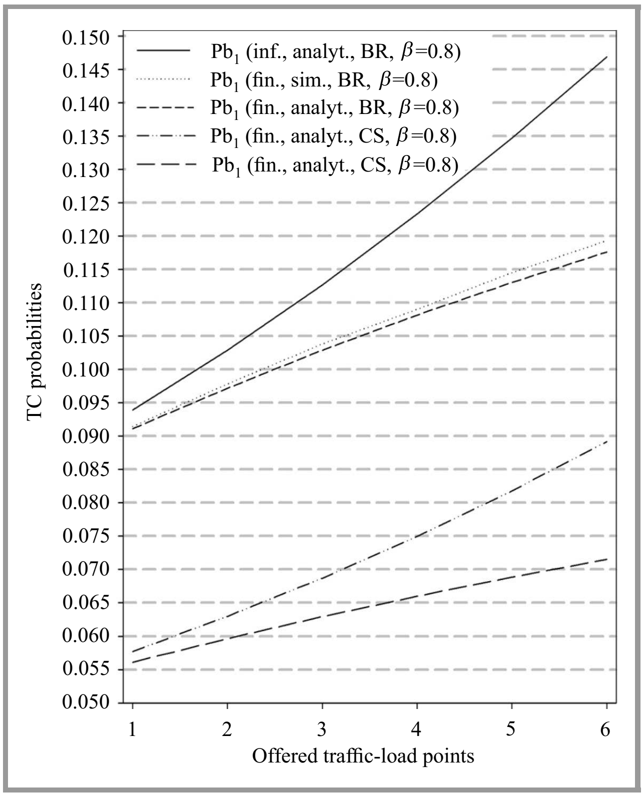

Fig. 4. TC probabilities – 1st service-class ($\beta = 0.8$).

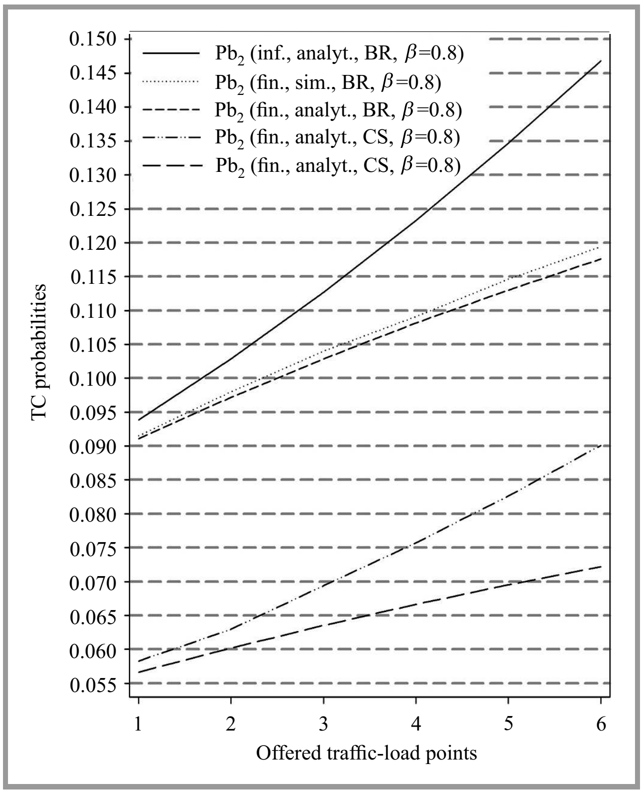

Fig. 6. TC probabilities – 2nd service-class ($\beta = 0.8$).

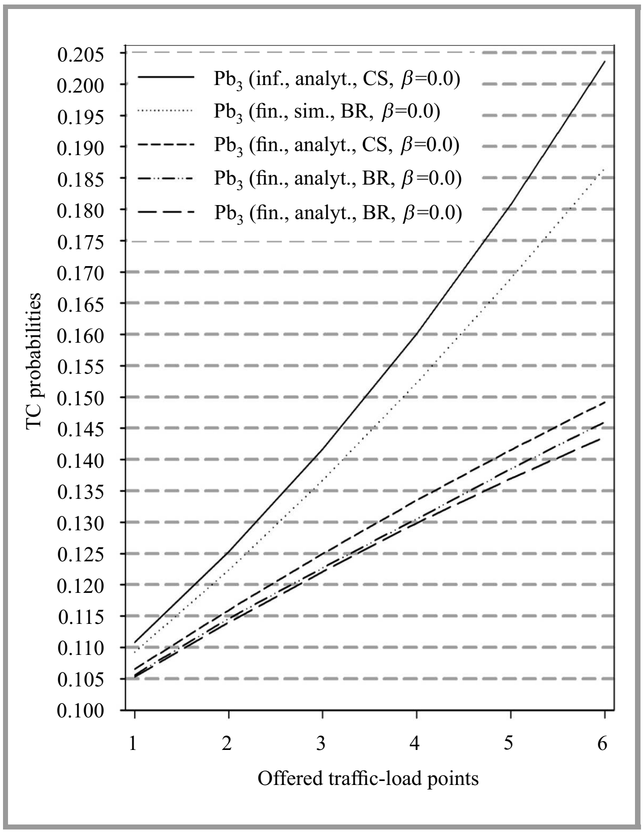

Fig. 7. TC probabilities – 3rd service-class ($\beta = 0$).

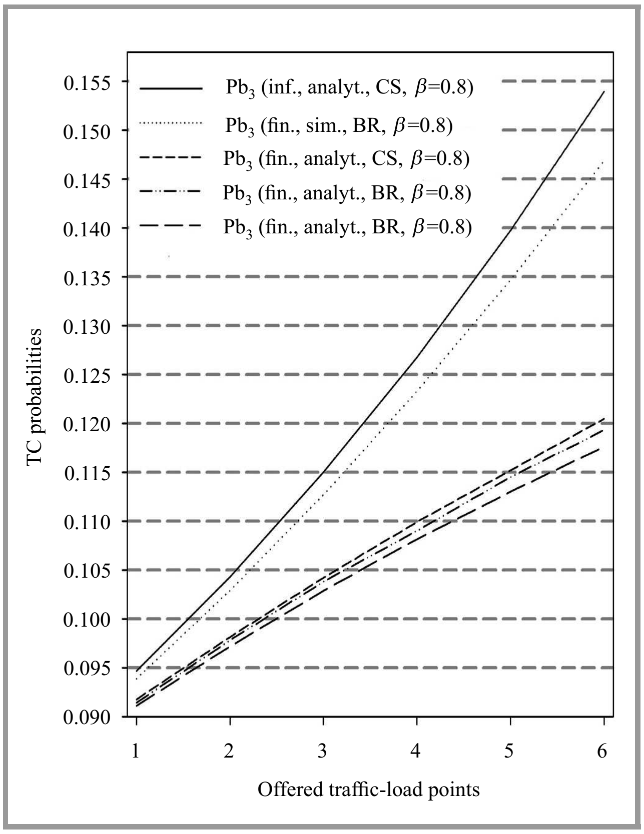

Fig. 8. TC probabilities – 3rd service-class ($\beta = 0.8$).

6. Conclusion

In this paper authors propose multirate loss models for the call-level analysis of a W-CDMA reference cell that supports calls from different service-classes with different bandwidth requirements. New call arrivals follow a Poisson arrival process, or a quasi-random arrival process. The proposed models take into account important peculiarities of wireless networks, such as multiple access interference, the notion of local blocking, user's activity, interference cancelation and the BR policy. The latter is used to achieve equalization of congestion probabilities among calls of different service-classes. Due to the existence of local blocking and the BR policy in the proposed models, the calculation of the occupancy distribution (and consequently of time and cal congestion probabilities) is based on an approximate but recursive formula. Simulation results verify the proposed model accuracy.

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