A Wireless Multirate Loss Model for Quasi-Random Traffic Under a State-dependent Threshold Policy

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***Abstract*– We consider a cell of certain capacity in a homogeneous wireless cellular network that accommodates new and handover calls from *K* service-classes and we assume that new calls follow a random or quasi-random process while handover calls follow a quasi-random process. The cell is analysed as a loss system. Calls are accepted in the cell based on a state-dependent bandwidth sharing policy. More precisely, if the number of in-service calls (new or handover) of a service-class exceeds a threshold (different for new and handover calls), then a new or handover arriving call of the same service-class is accepted in the cell with a predefined state-dependent probability. The proposed multirate loss model has a Product Form Solution (PFS) for the steady state probabilities. Based on the PFS, we propose a convolution algorithm for the accurate calculation of congestion probabilities. The accuracy of the proposed algorithm is verified through simulation and is highly satisfactory.**

I. INTRODUCTION

Quality of Service (QoS) mechanisms are essential in contemporary networks in order to provide access to the required bandwidth needed by services. Considering call-level traffic in a single cell which accommodates different service-classes with different QoS requirements, such a QoS mechanism is a bandwidth sharing policy. The latter affects call-level performance measures such as Call Blocking Probabilities (CBP).

The simplest bandwidth sharing policy is the classical Complete Sharing (CS) policy, where a new call is accepted in the cell simply if the call's bandwidth is available [1]. Due to this simple call admission mechanism, the CS policy cannot guarantee a certain QoS to a service-class, while it is unfair to calls of high bandwidth requirements, because it leads to higher CBP compared to calls of low bandwidth requirements (e.g., [2]-[11]). This unfairness motivates research on other policies, such as the Bandwidth Reservation (BR) policy (e.g., [12]-[26]) and the Threshold (TH) policy.

In this paper, we concentrate on the TH policy, because it is broadly applicable in wired (e.g., [27]-[33]) and wireless (e.g., [34]-[36]) networks. In the TH policy, a new call of a service-class k is blocked and lost (even if available bandwidth exists in the system) if upon its arrival the number of in-service service-class k calls plus the new call exceeds a threshold (dedicated to service-class k). We propose a state-dependent TH policy for a cell that accommodates quasi-random arriving calls of different service-classes. By the term "quasi-random", we refer to calls generated by a finite number of Mobile Users (MUs). In the proposed policy, the acceptance of a call (subject to bandwidth availability) above a threshold is permitted with a probability. This probability depends not only on the state of the system but also on the service-class of the new call. The proposed loss model has a Product Form Solution (PFS) for the steady state distribution. Thanks to the existence of the PFS, we can accurately determine congestion probabilities based on a convolution algorithm [37].

This paper is organized as follows: In Section II, we present the proposed policy, show the PFS and provide a convolution algorithm for the calculation of congestion probabilities. In Section III, we present the case where new calls follow a Poisson process and handover calls follow a quasi-random process. In Section IV, we present analytical congestion probability results both for the proposed model and the models of [38] (CS policy), [39] (BR policy), and [36] (TH policy) for evaluation. We conclude in Section IV.

II. THE PROPOSED MODEL FOR QUASI-RANDOM TRAFFIC

Consider a cell of fixed capacity C channels that accommodates quasi-random arriving calls under the proposed policy. To facilitate the presentation of the model, we separate new from handover calls of the same service-class. This means that the cell accommodates $2K$ service-classes. A service-class k call is new if $1 \le k \le K$ and handover if $K+1 \le k \le 2K$. A new service-class k call and a handover service-class $K+k$ call require the same number of channels, b_k. Service-class k calls (k =1,…,2K) come from a finite source population N_k. The effective arrival rate of service-class k calls is $\lambda_{k,fin} = (N_k - n_k)v_k$ where n_k is the number of in-service calls and v_k is the arrival rate per idle source. The offered traffic-load per idle service-class k source is $a_{k,fin} = v_k / \mu_k$ (in erl) where μ_k^{-1} is the mean service time (generally distributed) of an accepted service-class k call.

To describe the call admission mechanism, consider a service-class k call that requires b_k channels. If these channels are not available in the cell, then the call is blocked and lost; otherwise:

a) If the number n_k of in-service calls of service-class k (k =1,…,2K) in the steady state plus the new or handover call, does not exceed a threshold n_k^*, i.e., $n_k + 1 \le n_k^*$, then the call is accepted in the system.

b) If $n_k + 1 > n_k^*$, the call is accepted with probability $p_k(n_k)$ or blocked with probability 1- $p_k(n_k)$. The set of $p_k(n_k)$ is defined as:

$$\boldsymbol{p_k} = (p_k(0), p_k(1)..., p_k(n_k^*),..., p_k(\lfloor C/b_k \rfloor - 1), p_k(\lfloor C/b_k \rfloor)) \quad (1)$$

where $\lfloor C/b_k \rfloor$ is the maximum number of service-class k calls that can be serviced by the system.

In (1), we assume that: a) $p_k(0) = ... = p_k(n_k^* - 1) = 1$, i.e., a service-class k call is accepted if n_k^* is not exceeded, b) the probabilities $p_k(n_k^*),..., p_k(\lfloor C/b_k \rfloor - 1)$ may be different for new or handover calls of the same service-class k (in the TH policy [27], these probabilities are zero) and c) $p_k(\lfloor C/b_k \rfloor) = 0$ due to lack of bandwidth.

Let the steady state vector be $\boldsymbol{n} = (n_1,...,n_k,...,n_{2K})$, $\boldsymbol{n_k^-} = (n_1,...,n_k - 1,...,n_{2K})$, $\boldsymbol{n_k^+} = (n_1,...,n_k + 1,...,n_{2K})$ and $P_{fin}(\boldsymbol{n})$, $P_{fin}(\boldsymbol{n_k^-}), P_{fin}(\boldsymbol{n_k^+})$ are the probability distributions of states $\boldsymbol{n}, \boldsymbol{n_k^-}, \boldsymbol{n_k^+}$, respectively.

The Global Balance (GB) equation for state $\boldsymbol{n}$, expressed as *rate into state* $\boldsymbol{n}$ = *rate out of state* $\boldsymbol{n}$, is:

$$\sum_{k=1}^{2K}\left[(N_k - n_k + 1)v_k\delta_k^-(\boldsymbol{n})p_k(n_k - 1)P_{fin}(\boldsymbol{n_k^-}) + (n_k + 1)\mu_k\delta_k^+(\boldsymbol{n})P_{fin}(\boldsymbol{n_k^+})\right] =$$
$$\sum_{k=1}^{2K}\left[(N_k - n_k)v_k\delta_k^+(\boldsymbol{n})p_k(n_k)P_{fin}(\boldsymbol{n}) + n_k\mu_k\delta_k^-(\boldsymbol{n})P_{fin}(\boldsymbol{n})\right] \quad (2)$$

where: $\delta_k^+(\boldsymbol{n}) = \begin{cases} 1 & \text{if } \boldsymbol{n_k^+} \in \boldsymbol{\Omega} \\ 0 & \text{otherwise} \end{cases}$, $\delta_k^-(\boldsymbol{n}) = \begin{cases} 1 & \text{if } \boldsymbol{n_k^-} \in \boldsymbol{\Omega} \\ 0 & \text{otherwise} \end{cases}$,

$\boldsymbol{\Omega}$ is the state space of the system, $\boldsymbol{\Omega}$={$\boldsymbol{n}$: 0 $\le \boldsymbol{nb} \le C$, k=1,…,2K}and $\boldsymbol{nb} = \sum_{k=1}^{2K} n_k b_k$, $\boldsymbol{b} = (b_1,...,b_{2K})^T$.

The Markov chain of the proposed model is reversible and therefore, Local Balance (LB) exists between adjacent states. The form of LB equations, extracted as (*rate up = rate down*), for k =1,…,2K and $\boldsymbol{n} \in \boldsymbol{\Omega}$ is as follows:

$$(N_k - n_k + 1)v_k\delta_k^-(\boldsymbol{n})p_k(n_k - 1)P_{fin}(\boldsymbol{n_k^-}) = n_k\mu_k\delta_k^-(\boldsymbol{n})P_{fin}(\boldsymbol{n}) \quad (3)$$

$$(N_k - n_k)v_k\delta_k^+(\boldsymbol{n})p_k(n_k)P_{fin}(\boldsymbol{n}) = (n_k + 1)\mu_k\delta_k^+(\boldsymbol{n})P_{fin}(\boldsymbol{n_k^+}) \quad (4)$$

The system of LB equations is satisfied by the PFS:

$$P_{fin}(\boldsymbol{n}) = G^{-1}\left(\prod_{k=1}^{2K}\binom{N_k}{n_k}\prod_{x=n_k^*}^{n_k-1} p_k(x)a_{k,fin}^{n_k}\right) \quad (5)$$

where G is the normalization constant given by:

$$G \equiv G(\boldsymbol{\Omega}) = \sum_{\boldsymbol{n}\in\boldsymbol{\Omega}}\left(\prod_{k=1}^{2K}\binom{N_k}{n_k}\prod_{x=n_k^*}^{n_k-1} p_k(x)a_{k,fin}^{n_k}\right) \quad (6)$$

In a system with quasi-random input, CBP are distinguished to Time Congestion (TC) and Call Congestion (CC) probabilities. To calculate the TC probabilities of service-class k calls, B_k, let $\boldsymbol{\Omega}_k$={$\boldsymbol{n}$:0 $\le \boldsymbol{nb} \le C$-$b_k$, k=1,…,2K} be the state space which denotes the set of states for which a service-class k call will be definitely accepted or accepted with a state-dependent probability in the system. Thus:

$$B_k = 1 - G_k / G \quad (7)$$

where $G_k = \sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_k} p_k(n_k)P_{fin}(\boldsymbol{n})$.

CC probabilities, i.e., CBP seen by an arriving call, are calculated via (7) by considering N_k – 1 traffic sources. Note that in the case of random input, CC and TC probabilities coincide. In that case, we use the term CBP.

For an efficient calculation of TC or CC probabilities we exploit (5) and use a 3-step convolution algorithm:

Define j as the occupied bandwidth, j = 0, 1,…,C.

Step 1) Determine the occupancy distribution $q_k(j)$ of each service-class k (k=1,…,2K), assuming that only service-class k exists in the system:

$$q_k(j) = \left\langle \begin{array}{ll} q_k(0)\binom{N_k}{i}a_{k,fin}^i & ,for\ 1 \le i \le n_k^*\ and\ j = ib_k \\ q_k(0)\binom{N_k}{i}\prod_{x=n_k^*}^{i-1} p_k(x)a_{k,fin}^i & ,for\ n_k^* < i \le \lfloor C/b_k \rfloor and\ j = ib_k \\ 0 & ,otherwise \end{array} \right\rangle \quad (8)$$

Step 2) Determine the aggregated occupancy distribution $Q_{(-k)}$ based on the successive convolution of all service-classes apart from service-class k:

$$Q_{(-k)} = q_1 * ... * q_{k-1} * q_{k+1} * ... * q_{2K}$$

The term "successive" means that we initially convolve q_1 and q_2 to obtain q_{12}. Then we convolve q_{12} with q_3 to obtain q_{123} etc. The convolution operation between q_k and q_r is defined as:

$$q_k * q_r = \left\{q_k(0)q_r(0), \sum_{x=0}^{1} q_k(x)q_r(1-x),..., \sum_{x=0}^{C} q_k(x)q_r(C-x)\right\} \quad (9)$$

Step 3) Calculate the TC probabilities of service-class k based on the convolution of $Q_{(-k)}$ and q_k as follows:

$$Q_{(-k)} * q_k = \left\{Q_{(-k)}(0)q_k(0), \sum_{x=0}^{1} Q_{(-k)}(x)q_k(1-x),..., \sum_{x=0}^{C} Q_{(-k)}(x)q_k(C-x)\right\} \quad (10)$$

Normalizing the values of (10), we obtain the occupancy distribution $q(j)$, j=0,1,…,C via:

$$q(0) = Q_{(-k)}(0)q_k(0)/G$$
$$q(j) = \left(\sum_{x=0}^{j} Q_{(-k)}(x)q_k(j-x)\right)\Big/G,\ j = 1,...,C \quad (11)$$

Based on $q(j)$'s, we propose the following formula for the TC probabilities of service-class k:

$$B_k = \sum_{j=C-b_k+1}^{C} q(j) + \sum_{x=n_k^* b_k}^{C-b_k}(1 - p_k(x))q_k(x)\sum_{y=x}^{C-b_k} Q_{(-k)}(C - b_k - y) \quad (12)$$

The first term of (12) refers to states j where there is no bandwidth available for service-class k calls. The second term refers to states $x = n_k^* b_k,..., C - b_k$ where there is

available bandwidth for service-class k calls but call blocking occurs due to the proposed policy.

If $N_k \to \infty$ for $k = 1,...,2K$ and the total offered traffic remains constant, then a Poisson process arises and we have the model of [36] whose PFS is the following:

$$P(\boldsymbol{n}) = G^{-1}\left(\prod_{k=1}^{2K}\prod_{x=n_k^*}^{n_k-1} p_k(x)\frac{a_k^{n_k}}{n_k!}\right) \quad (13)$$

where $a_k = \lambda_k \mu_k^{-1}$ is the offered traffic-load (in erl) of service-class k calls and G is the normalization constant:

$$G \equiv G(\boldsymbol{\Omega}) = \sum_{\boldsymbol{n}\in\boldsymbol{\Omega}}\left(\prod_{k=1}^{2K}\prod_{x=n_k^*}^{n_k-1} p_k(x)\frac{a_k^{n_k}}{n_k!}\right).$$

For the CBP calculation, we exploit (13) and use the aforementioned 3-step convolution algorithm, whereby the only change is in (8) which becomes [36]:

$$q_k(j) = \left\langle \begin{array}{l} q_k(0)\dfrac{a_k^i}{i!} \quad , for\ 1 \le i \le n_k^*\ and\ j = ib_k \\ q_k(0)\dfrac{\prod_{x=n_k^*}^{i-1} p_k(x) a_k^i}{i!} \quad , for\ n_k^* < i \le \lfloor C/b_k \rfloor and\ j = ib_k \end{array} \right\rangle \quad (14)$$

III. The Proposed Model for Random/Quasi-Random Traffic

A special case of the previous model is the model whereby new calls follow a Poisson process and handover calls a quasi-random process. In that case, we can extract the following LB equations:

$$\lambda_k \delta_k^-(\boldsymbol{n}) p_k(n_k - 1) P_{inf,fin}(\boldsymbol{n}_k^-) = n_k \mu_k \delta_k^-(\boldsymbol{n}) P_{inf,fin}(\boldsymbol{n}), 1 \le k \le K \quad (15)$$

$$\begin{aligned} &(N_k - n_k + 1) v_k \delta_k^-(\boldsymbol{n}) p_k(n_k - 1) P_{inf,fin}(\boldsymbol{n}_k^-) \\ &= n_k \mu_k \delta_k^-(\boldsymbol{n}) P_{inf,fin}(\boldsymbol{n}),\ K+1 \le k \le 2K \end{aligned} \quad (16)$$

$$\lambda_k \delta_k^+(\boldsymbol{n}) p_k(n_k) P_{inf,fin}(\boldsymbol{n}) = (n_k + 1)\mu_k \delta_k^+(\boldsymbol{n}) P_{inf,fin}(\boldsymbol{n}_k^+), 1 \le k \le K \quad (17)$$

$$\begin{aligned} &(N_k - n_k) v_k \delta_k^+(\boldsymbol{n}) p_k(n_k) P_{inf,fin}(\boldsymbol{n}) = \\ &(n_k + 1)\mu_k \delta_k^+(\boldsymbol{n}) P_{inf,fin}(\boldsymbol{n}_k^+),\ K+1 \le k \le 2K \end{aligned} \quad (18)$$

This system of LB equations is satisfied by the PFS:

$$P_{inf,fin}(\boldsymbol{n}) = G^{-1}\left[\prod_{k=1}^{K}\left(\frac{a_k^{n_k}}{n_k!}\prod_{x=n_k^*}^{n_k-1} p_k(x)\right)\prod_{k=K+1}^{2K}\left(\binom{N_k}{n_k} a_{k,fin}^{n_k}\prod_{y=n_k^*}^{n_k-1} p_k(y)\right)\right] \quad (19)$$

where G is the normalization constant given by:

$$\begin{aligned} &G \equiv G(\boldsymbol{\Omega}) \\ &= \sum_{\boldsymbol{n}\in\boldsymbol{\Omega}}\left[\prod_{k=1}^{K}\left(\frac{a_k^{n_k}}{n_k!}\prod_{x=n_k^*}^{n_k-1} p_k(x)\right)\prod_{k=K+1}^{2K}\left(\binom{N_k}{n_k} a_{k,fin}^{n_k}\prod_{y=n_k^*}^{n_k-1} p_k(y)\right)\right] \end{aligned} \quad (20)$$

For an efficient calculation of congestion probabilities, we exploit (19) and use the 3-step algorithm of Section II, whereby, $q_k(j)$'s for new and handover service-class k calls are given by (14) and (8), respectively.

IV. Numerical Results

In this section we present analytical results for an application example. Simulation results are mean values of 7 runs and are almost identical to the corresponding analytical results. The simulation tool used is Simscript III [40].

We consider a cell of capacity C=150 channels that accommodates two service-classes, with the traffic characteristics as shown in Table I:

Table I: Traffic characteristics

Service-class	Traffic-load (erl)	Bandwidth (channels)	Threshold	Sources	Traffic-load per idle source (erl)
1st (new)	a_1= 20.0	b_1 = 2	n_1^* = 35	100	$a_{1,fin}$ = 0.20
2nd (new)	a_2 = 5.0	b_2 = 7	n_2^* = 10	100	$a_{2,fin}$ = 0.05
1st (handover)	a_3 = 6.0	b_3 = 2	n_3^* = 70	100	$a_{3,fin}$ = 0.06
2nd (handover)	a_4 = 1.0	b_4 = 7	n_4^* = 20	100	$a_{4,fin}$ = 0.01

We provide analytical and simulation TC probabilities results for the proposed random/quasi-random model considering two scenarios: (1) New calls of the 1st service-class behave as in the ordinary TH policy, i.e., $p_1(35) = p_1(36) = ... = p_1(75) = 0$, while new calls of the 2nd service-class are accepted in the system with probability $p_2(10) = ... = p_2(20) = 0.5$, and $p_2(21) = 0$, (2) New calls of the 1st service-class are accepted in the system with probability $p_1(35) = ... = p_1(74) = 0.7$, and $p_1(75) = 0$ while new calls of the 2nd service-class are accepted as in scenario 1. For both scenarios, we assume that $p_3() = p_4() = 0.95$, for all possible states equal or above the corresponding thresholds. These TC probabilities results are compared with the TC probabilities: a) of random new and handover traffic and the CS policy [38], the BR policy [39] and the threshold policy of [36] and b) for random new and quasi-random handover traffic and the CS or the BR policy [41]. In the BR policy, the values of the BR parameters are $t_1 = t_3 = 5$ channels and $t_2 = t_4 = 0$ so as to achieve equalization of TC probabilities among calls (new or handover) of both service-classes. The BR parameters of a service-class k denote the number of channels reserved to benefit calls of all service-classes, apart from k. In the x-axis of Figs 1-4 the offered traffic load of new and handover calls of both service-classes increases in steps of 1.0, 0.2, 0.5 and 0.1 erl, respectively. So, point 1 refers to: (a_1, a_2, a_3, a_4) = (20.0, 5.0, 6.0, 1.0) while point 11 to: (a_1, a_2, a_3, a_4) = (30.0, 7.0, 11.0, 2.0).

Figures 1-4 show that: a) The proposed policy affects the TC probabilities; thus, it allows for a fine congestion control aiming at guaranteeing QoS to each service-class. (b) The TC probabilities obtained for random handover traffic are higher compared to the corresponding results obtained for quasi-random handover traffic. This is anticipated due to the finite number of traffic sources in the case of quasi-random traffic. (c) The existing CS and BR policies fail to approximate the results obtained from the proposed policy.

V. CONCLUSION

We propose a teletraffic multirate loss model for a single cell that accommodates quasi-random traffic under a state-dependent threshold-based bandwidth sharing policy. The link is analysed as a multirate loss system, via a reversible continuous-time Markov chain, which leads to a PFS for the steady state distribution. Based on the PFS, congestion probabilities can be accurately determined via a convolution algorithm. Comparison against other models under the CS, the BR or the TH policy, reveals the necessity of the new model.

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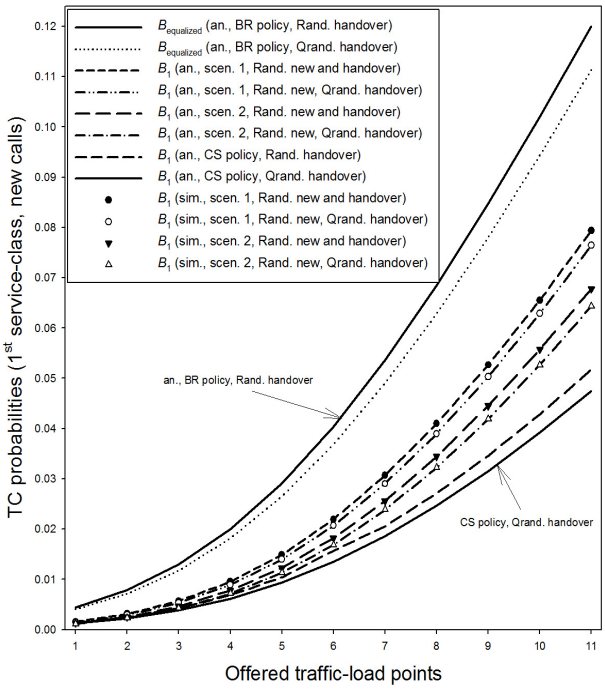

Fig. 1. TC probabilities – 1st service-class (new calls).

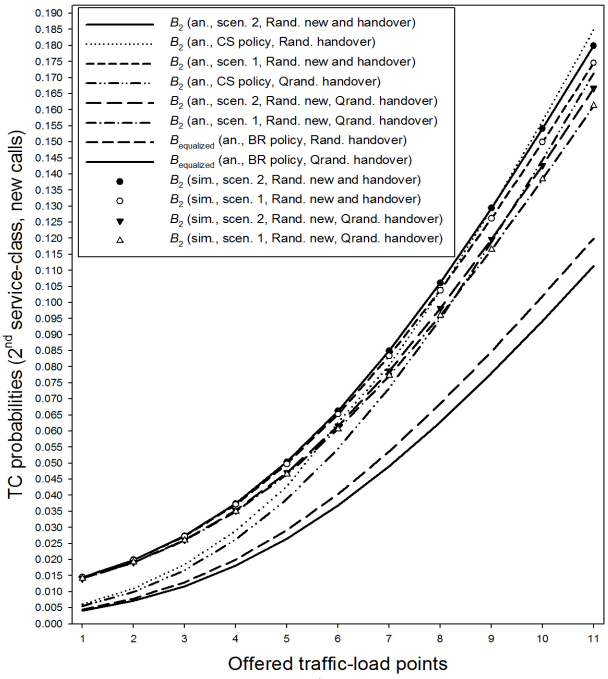

Fig. 2. TC probabilities – 2nd service-class (new calls).

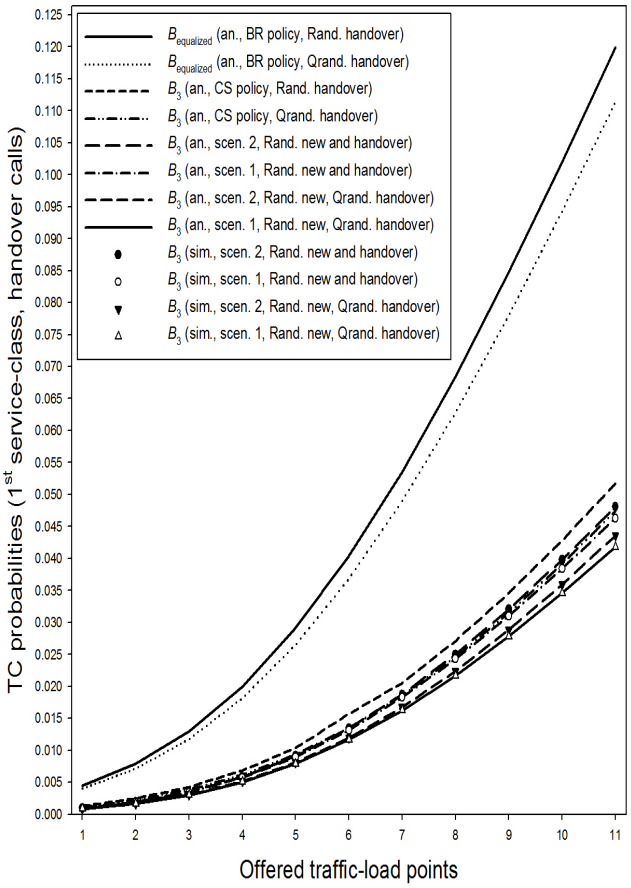

Fig. 3. TC probabilities – 1st service-class (handover calls).

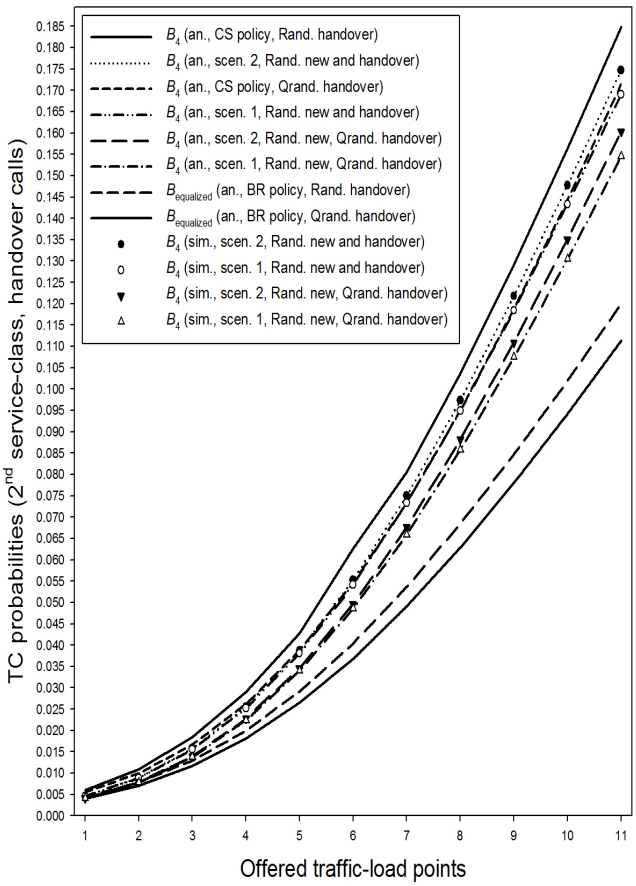

Fig. 4. TC probabilities – 2nd service-class (handover calls).