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

# I. D. Moscholios

Dept. of Informatics & Telecommunications, University of Peloponnese, 221 00 Tripolis, Greece. E-mail: idm@uop.gr

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 ${\it TRAFFIC}$

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 kcalls (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  $\mu_k^{-1}$  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:

$$\mathbf{p}_{k} = (p_{k}(0), p_{k}(1)..., p_{k}(n_{k}^{*}),..., p_{k}(|C/b_{k}|-1), p_{k}(|C/b_{k}|))$$
(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  $\mathbf{n} = (n_1, ..., n_k, ..., n_{2K})$ ,  $\mathbf{n}_k^- = (n_1, ..., n_k - 1, ..., n_{2K})$ ,  $\mathbf{n}_k^+ = (n_1, ..., n_k + 1, ..., n_{2K})$  and  $P_{fin}(\mathbf{n})$ ,  $P_{fin}(\mathbf{n}_k^-)$ ,  $P_{fin}(\mathbf{n}_k^+)$  are the probability distributions of states  $\mathbf{n}$ ,  $\mathbf{n}_k^-$ ,  $\mathbf{n}_k^+$ , respectively.

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

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

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

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

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

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  $n \in \Omega$  is as follows:

$$(N_{k}-n_{k}+1)v_{k}\delta_{k}(\mathbf{n})p_{k}(n_{k}-1)P_{fin}(\mathbf{n}_{k})=n_{k}\mu_{k}\delta_{k}(\mathbf{n})P_{fin}(\mathbf{n})$$
(3)

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

The system of LB equations is satisfied by the PFS:

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

where G is the normalization constant given by:

$$G \equiv G(\mathbf{\Omega}) = \sum_{n \in \mathbf{\Omega}} \left( \prod_{k=1}^{2K} \binom{N_k}{n_k} \prod_{x=n_k^*}^{n_k-1} p_k(x) a_{k,fin}^{n_k} \right)$$
(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  $\Omega_k = \{n: 0 \le nb \le C-b_k, k=1,...,2K\}$  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:

$$B_k = 1 - G_k / G \tag{7}$$

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

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:

$$q_{k}(j) = \begin{pmatrix} q_{k}(0) \binom{N_{k}}{i} d_{k,fin}^{j} & \text{, for } 1 \leq i \leq n_{k}^{*} \text{ and } j = ib_{k} \\ q_{k}(j) = \begin{pmatrix} q_{k}(0) \binom{N_{k}}{i} \prod_{x=n_{k}}^{j-1} p_{k}(x) d_{k,fin}^{j} & \text{, for } n_{k}^{*} < i \leq \lfloor C/b_{k} \rfloor \text{ and } j = ib_{k} \\ 0 & \text{, otherwise} \end{pmatrix}$$
(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:

$$q_{k} * q_{r} = \left\{ q_{k}(0)q_{r}(0), \sum_{k=0}^{1} q_{k}(x)q_{r}(1-x), \dots, \sum_{k=0}^{C} q_{k}(x)q_{r}(C-x) \right\}$$
(9)

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

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

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

$$q(0) = Q_{(-k)}(0)q_k(0)/G$$

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

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

$$B_{k} = \sum_{j=C-b_{k}+1}^{C} q(j) + \sum_{x=n_{k}b_{k}}^{C-b_{k}} (1-p_{k}(x))q_{k}(x) \sum_{y=x}^{C-b_{k}} Q_{(-k)}(C-b_{k}-y)$$
 (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:

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

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

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]:

$$q_{k}(j) = \begin{pmatrix} q_{k}(0)\frac{d_{k}^{j}}{i!} & \text{, for } 1 \leq i \leq n_{k}^{*} \text{ and } j = ib_{k} \\ \prod_{i=1}^{j-1} p_{k}(x)d_{k}^{j} \\ q_{k}(0)\frac{\sum_{x=n_{k}^{*}} p_{k}(x)d_{k}^{j}}{i!} & \text{, for } n_{k}^{*} < i \leq \lfloor C/b_{k} \rfloor \text{ and } j = ib_{k} \end{pmatrix}$$

$$(14)$$

# 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:

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

$$(N_k - n_k + 1)v_k \delta_k^-(\mathbf{n}) p_k(n_k - 1) P_{inf,fin}(\mathbf{n}_k^-)$$

$$= n_k \mu_k \delta_k^-(\mathbf{n}) P_{inf,fin}(\mathbf{n}), K + 1 \le k \le 2K$$
(16)

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

$$(N_k - n_k) v_k \delta_k^+(\boldsymbol{n}) p_k(n_k) P_{inf,fin}(\boldsymbol{n}) =$$

$$(n_k + 1) \mu_k \delta_k^+(\boldsymbol{n}) P_{inf,fin}(\boldsymbol{n}_k^+), K + 1 \le k \le 2K$$

$$(18)$$

This system of LB equations is satisfied by the PFS:

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

where G is the normalization constant given by:

$$G \equiv G(\Omega)$$

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

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-	Bandwidth	Threshold	Sources	Traffic-load
	load	(channels)			per idle
	(erl)				source
					(erl)
1 <sup>st</sup> (new)	$a_1 = 20.0$	$b_1 = 2$	$n_{\rm l}^* = 35$	100	$a_{1,\text{fin}} = 0.20$
2 <sup>nd</sup> (new)	$a_2 = 5.0$	b <sub>2</sub> = 7	$n_2^* = 10$	100	$a_{2,\text{fin}} = 0.05$
1st (handover)	$a_3 = 6.0$	$b_3 = 2$	$n_3^* = 70$	100	$a_{3,\text{fin}} = 0.06$
2 <sup>nd</sup> (handover)	$a_4 = 1.0$	b <sub>4</sub> = 7	$n_4^* = 20$	100	$a_{4,\text{fin}} = 0.01$

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.,  $p_1(35) = p_1(36) = \dots = p_1(75) = 0$ , while new calls of the 2<sup>nd</sup> 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  $p_1(35) = \dots = p_1(74) = 0.7$ , and  $p_1(75) = 0$  while new calls of the 2<sup>nd</sup> 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 probabilities results are compared with the 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 kdenote 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.

### REFERENCES

- M. Stasiak, M. Glabowski, A.Wisniewski, and P. Zwierzykowski, Modeling and Dimensioning of Mobile Networks, Wiley, 2011.
- S. Rácz, B. Gerő, and G. Fodor, "Flow level performance analysis
  of a multi-service system supporting elastic and adaptive
  services", Performance Evaluation, 49 (1-4), pp. 451-469,
  September 2002.
- V. Iversen, V. Benetis, N. Ha, S. Stepanov, "Evaluation of Multiservice CDMA Networks with Soft Blocking", Proc. of ITC Specialist Seminar, Antwerp, Belgium, pp. 223-227, August/September 2004.
- I. Moscholios, M. Logothetis and M. Koukias, "An ON-OFF Multirate Loss Model of Finite Sources", IEICE Transactions on Communications, E90-B (7), pp. 1608-1619, July 2007.
- Y. Deng and P. Prucnal, "Performance analysis of heterogeneous optical CDMA networks with bursty traffic and variable power control", IEEE/OSA Journal of Optical Communications and Networking, 3 (6), pp. 487-492, June 2011.
- M. Stasiak, D. Parniewicz and P. Zwierzykowski, "Traffic Engineering for Multicast Connections in Multiservice Cellular Network", IEEE Transactions on Industrial Informatics, 9 (1), pp. 262 – 270, February 2013.
- I. Moscholios, G. Kallos, V. Vassilakis and M. Logothetis, "Congestion Probabilities in CDMA-based networks supporting batched Poisson input traffie", Wireless Personal Communications, 79 (2), pp. 1163-1186, November 2014.
- V. Vassilakis, I. Moscholios and M. Logothetis, "Uplink Blocking Probabilities in Priority-Based Cellular CDMA Networks with Finite Source Population", IEICE Transactions on Communications, E99-B (6), pp. 1302-1309, June 2016.
- S. Hanczewski, A. Kaliszan and M. Stasiak, "Convolution model of a queueing system with the cFIFO service discipline", Mobile Information Systems, volume 2016, Article ID 2185714, 15 pages.
- V. Vassilakis, I. Moscholios and M. Logothetis, "Quality of Service Differentiation of Elastic and Adaptive Services in CDMA Networks: A Mathematical Modelling Approach", accepted for publication in Wireless Networks, 2017.
- I. Moscholios, M. Logothetis and S. Shioda, "Performance Evaluation of Multirate Loss Systems Supporting Cooperative Users with a Probabilistic Behavior", accepted for publication in IEICE Trans. Commun., E100-B (10), October 2017.
- M. Stasiak, M. Glabowski, "A simple approximation of the link model with reservation by a one-dimensional Markov chain", Performance Evaluation, 41 (2-3), pp. 195-208, July 2000.
- F. Cruz-Pérez, J. Vázquez-Ávila and L. Ortigoza-Guerrero, "Recurrent formulas for the multiple fractional channel reservation strategy in multi-service mobile cellular networks", IEEE Communications Letters, 8 (10), pp. 629-631, October 2004.
- 14. M. Glabowski, A. Kaliszan and M. Stasiak, "Asymmetric convolution algorithm for blocking probability calculation in full-availability group with bandwidth reservation", IET Circuits, Devices & Systems, 2 (1), pp. 87-94, February 2008.
- M. Glabowski, "Modelling of state-dependent multirate systems carrying BPP traffic", Annals of Telecommunications, 63 (7), pp. 393-407, August 2008.
- M. Stasiak, P. Zwierzykowski, D. Parniewicz, "Modelling of the WCDMA Interface in the UMTS Network with Soft Handoff Mechanism", Proc. IEEE Globecom, Honolulu, November 2009.

- 17. Q. Huang, K. Ko and V. Iversen, "A new convolution algorithm for loss probability analysis in multiservice networks", Performance Evaluation, 68 (1), pp. 76-87, January 2011.
- I. Moscholios, J. Vardakas, M. Logothetis and A. Boucouvalas, "A Batched Poisson Multirate Loss Model Supporting Elastic Traffic under the Bandwidth Reservation Policy", Proc. IEEE ICC, Kyoto, Japan, June 2011.
- I. Moscholios, J. Vardakas, M. Logothetis and A. Boucouvalas, "QoS Guarantee in a Batched Poisson Multirate Loss Model Supporting Elastic and Adaptive Traffic", Proc. IEEE ICC, Ottawa, Canada, June 2012.
- M. Glabowski, M. Sobieraj and M. Stasiak, "Modelling Limitedavailability Systems with Multi-service Sources and Bandwidth Reservation", Proc. 8th AICT, Stuttgart, Germany, June 2012.
- V. Vassilakis, I. Moscholios and M. Logothetis, "The Extended Connection-Dependent Threshold Model for Call-level Performance Analysis of Multi-rate Loss Systems under the Bandwidth Reservation Policy", Int. Journal of Communication Systems, 25 (7), pp. 849-873, July 2012.
- I. Moscholios, V. Vassilakis, M. Logothetis and M. Koukias, "QoS Equalization in a Multirate Loss Model of Elastic and Adaptive Traffic with Retrials", Proc. 5th EMERGING, Porto, Portugal, October 2013.
- I. Moscholios, J. Vardakas, M. Logothetis and M. Koukias, "A Quasi-random Multirate Loss Model supporting Elastic and Adaptive Traffic under the Bandwidth Reservation Policy", Int. Journal on Advances in Networks and Services, 6 (3&4), pp. 163-174, December 2013.
- 24. L. Brewka, V. Iversen and G. Kardaras, "Integrated service resource reservation using queueing networks", IET Networks, 3 (1), pp. 16-21, March 2014.
- F. Callegati, et al., "Trunk reservation for fair utilization in flexible optical networks", IEEE Communications Letters, 18 (5), pp. 889-892, May 2014.
- 26. I. Moscholios, V. Vassilakis, G. Kallos and M. Logothetis, "Performance analysis of CDMA-based networks with interference cancellation, for batched Poisson traffic under the bandwidth reservation policy", Proc. of Int. Conf. on Telecommun., ConTEL 2015, Graz, Austria, 13-15 July 2015.
- D. Tsang and K. Ross, "Algorithms to determine exact blocking probabilities for multirate tree networks", IEEE Transactions on Communications, 38 (8), pp. 1266-1271, August 1990.
- J. Ni, D. Tsang, S. Tatikonda and B. Bensaou, "Optimal and Structured Call Admission Control Policies for Resource-Sharing Systems", IEEE Transactions on Communications, 55 (1), pp. 158-170, January 2007.
- A. Al Daoud, M Alanyali and D. Starobinski, "On equilibrium analysis of acyclic multiclass loss networks under admission control", Operations Research Letters, 39 (6), pp. 406-410, November 2011.
- I. Moscholios, M. Logothetis, J. Vardakas and A. Boucouvalas, "Performance Metrics of a Multirate Resource Sharing Teletraffic Model with Finite Sources under both the Threshold and Bandwidth Reservation Policies", IET Networks, 4 (3), pp. 195-208, May 2015.
- I. Moscholios, M. Logothetis, A. Boucouvalas and V. Vassilakis, "An Erlang Multirate Loss Model Supporting Elastic Traffic under the Threshold Policy", Proc. IEEE ICC, London, U.K., June 2015.
- 32. A. Ali, S. Wei and L. Qian, "Optimal admission and preemption control in finite source loss systems", Operations Research Letters, 43 (3), pp. 241-246, May 2015.
- I. Moscholios, M. Logothetis and A. Boucouvalas, "Blocking Probabilities of Elastic and Adaptive Calls in the Erlang Multirate Loss Model under the Threshold Policy", Telecommunication Systems, 62 (1), pp. 245-262, May 2016.
- A. Al Daoud, M. Alanyali and D. Starobinski, "Pricing strategies for spectrum lease in secondary markets", IEEE/ACM Transactions on Networking, 18 (2), pp. 462–475, April 2010.
- X. Y. Yu and H. B. Zhu, "An efficient method for loss performance modeling of hierarchical heterogeneous wireless networks", Int. Journal of Communication Systems, 27 (6), pp. 956-968, June 2014.

- 36. I. Moscholios, V. Vassilakis, M. Logothetis and A. Boucouvalas, "A Probabilistic Threshold-based Bandwidth Sharing Policy for Wireless Multirate Loss Networks", IEEE Wireless Communications Letters, vol. 5, issue 3, pp 304-307, June 2016.
- V. Iversen, "The exact evaluation of multi-service loss system with access control", Teleteknik, 31 (2), pp. 56–61, August 1987.
- J. Kaufman, "Blocking in a shared resource environment", IEEE Trans. Commun., 29 (10), pp. 1474-1481, October 1981.
- 39. J. Roberts, "Teletraffic models for the Telecom 1 Integrated Services Network", Proc.  $10^{th}$  ITC, paper 1.1-2, Montreal 1983.
- 40. Simscript III, http://www.simscript.com
- I. Moscholios and M. Logothetis, "Engset Multirate State-Dependent Loss Models with QoS Guarantee", International Journal of Communications Systems, 19 (1), pp. 67-93, February 2006.

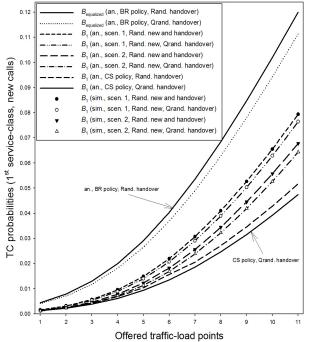


Fig. 1. TC probabilities – 1st service-class (new calls).

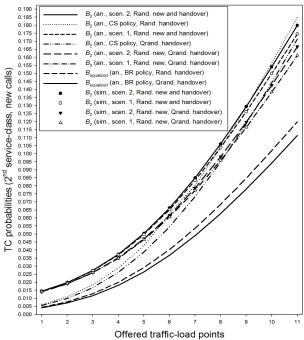


Fig. 2. TC probabilities – 2<sup>nd</sup> service-class (new calls).

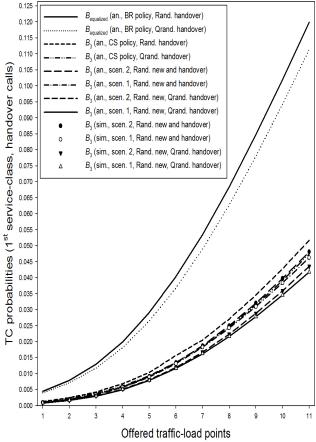


Fig. 3. TC probabilities – 1<sup>st</sup> service-class (handover calls).

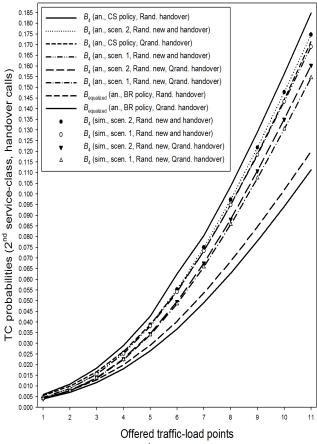


Fig. 4. TC probabilities  $-2^{nd}$  service-class (handover calls).