A Quasi-random Multirate Loss Model supporting Elastic and Adaptive Traffic

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Abstract— **Nowadays, the telecom network traffic environment is composed mostly of emerging multirate services whose calls can tolerate bandwidth compression either by extending their service-time (elastic services) or not (adaptive services). The co-existence of elastic and adaptive services makes the call-level performance analysis and evaluation of modern networks much more complicated. To contribute, in this paper, we present a new multirate loss model for elastic and adaptive services with finite traffic-source population. Thus, the call arrival process is a quasi-random process which is, in many cases, a more realistic consideration than a random (Poisson) process. The proposed model does not have a product form solution, and therefore, we propose approximate but recursive formulas for the efficient calculation of the call-level performance metrics, such as time and call congestion probabilities and link utilization. The consistency and the accuracy of the new model are verified through simulation and found to be quite satisfactory.**

Keywords - quasi-random process; elastic-adaptive traffic; recursive formula; time-call congestion; Markov chain.

I. INTRODUCTION

In modern communication networks, the increase of elastic and adaptive multirate traffic necessitates the QoS network assessment through proper teletraffic loss models [1]. Based on them, we can accommodate various services in the network according to their offered traffic-load, and avoid costly over-dimensioning of the links. By the term elastic traffic (e.g., file transfer) we refer to calls that can compress their bandwidth, while simultaneously expanding their service time. On the other hand, adaptive traffic refers to calls that can tolerate bandwidth compression, but their service time does not alter (e.g., adaptive video) [2].

Call-level multirate loss models of a single link of fixed capacity, where calls of both elastic and adaptive service-classes are accommodated, have been proposed in [2]-[4]. In all cases, calls can tolerate bandwidth compression down to a minimum value. In [2], calls arrive in the link according to a Poisson process (a random process) and use their peak bandwidth requirement when the occupied link bandwidth does not exceed the capacity of the link. Otherwise, the link accepts a call by compressing its peak-bandwidth, as well as the bandwidth of all in-service calls, at the same time. Call blocking occurs when, after the maximum possible bandwidth compression, the minimum bandwidth requirement of a new call is still higher than the available link bandwidth. The minimum bandwidth requirement of a call is a proportion of its peak-bandwidth; this proportion is common to all service-classes. When an in-service call, whose bandwidth has been compressed, departs from the system, then the remaining in-service calls expand their bandwidth. Our analysis through Markov chains shows that this bandwidth compression/ expansion destroys the Markov chain reversibility, and therefore no Product Form Solution (PFS) exists. However, based on the method proposed in [2], we find an approximate but reversible Markov chain, which is solved and leads to a recursive formula for the determination of link occupancy distribution and, consequently, call blocking probabilities and link utilization. This formula resembles the well-known Kaufman-Roberts formula used in the Erlang Multirate Loss Model (EMLM), where Poisson arriving calls of different service-classes have fixed bandwidth requirements (stream traffic) [6],[7]; thus, we name the model of [2], Extended EMLM (E-EMLM). In [3], the E-EMLM is extended to include retrials, i.e., blocked calls may retry one or more times to be serviced with reduced bandwidth. In [4], new calls, upon their arrival, may reduce their bandwidth according to the occupied link bandwidth. In [5], the E-EMLM is further extended to include the Batched Poisson call arrival process which is used to approximate arrival processes that are more "peaked" and "bursty" than the Poisson process. Recently, a multirate loss model that includes stream, elastic and adaptive traffic has been proposed in [8]; the presence of stream traffic prohibits the recursive calculation of link occupancy distribution.

In this paper, we extend [2] by assuming that calls of each service-class (elastic or adaptive) come from finite sources. This arrival process is known as quasi-random and is smoother than the Poisson process [9]. The proposed model does not have a PFS. However, we propose an approximate recursive formula for the efficient calculation of the link occupancy distribution. This formula simplifies the determination of: a) Time Congestion (TC) probabilities, b) Call Congestion (CC) probabilities and c)

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link utilization. Applications of the proposed model are in the area of wireless networks, where calls come from finite sources and their bandwidth is compressed (e.g., [10]-[12]).

The remainder of this paper is as follows: In Section II, we: a) present the basic assumptions of the proposed model and the call admission control, b) prove the recursive formula for the link occupancy distribution and c) provide formulas for the various performance measures. In Section III, we provide numerical results whereby the new model is compared to the E-EMLM and evaluated through simulation results. We conclude in Section IV.

II. THE PROPOSED MODEL

A. Basic assumptions and description of call admission

Consider a link of certain capacity C bandwidth units (b.u.) that accommodates elastic and adaptive calls of K different service-classes. Let K_e and K_a be the set of elastic and adaptive service-classes ($K_e + K_a = K$), respectively. Calls of service-class k (k=1,…,K) come from a finite source population N_k and request b_k b.u. (peak-bandwidth requirement). The mean arrival rate of service-class k idle sources is $\lambda_k = (N_k - n_k)v_k$ where n_k is the number of in-service calls and v_k is the arrival rate per idle source. This call arrival process is a quasi-random process [9]. If $N_k \to \infty$ for k=1,…,K then a Poisson process results. To introduce bandwidth compression, the occupied link bandwidth j may exceed C up to T b.u.

To describe call admission, consider the arrival of a service-class k call while the system is in state j. Then:

i) If $j + b_k \leq C$, the call is accepted in the system with its peak-bandwidth requirement for an exponentially distributed service time with mean μ_k^{-1}.

ii) If $j + b_k > T$, the call is blocked and lost.

iii) If $T \geq j + b_k > C$, the call is accepted in the system by compressing its peak-bandwidth requirement, as well as the assigned bandwidth of all in-service calls. All calls share the C b.u. in proportion to their peak-bandwidth requirement, while the link operates at its full capacity C. This is the processor sharing discipline [13].

When $T \geq j + b_k > C$, the compressed bandwidth b_k^{comp} of the newly accepted call, is given by:

$$b_k^{comp} = r b_k = \frac{C}{j'} b_k \tag{1}$$

where $r = C/j'$ denotes the compression factor, $j' = j + b_k$.

Since $j = \sum_{k=1}^{K} n_k b_k = \boldsymbol{nb}$, $\boldsymbol{n} = (n_1, n_2, ..., n_K)$ and $\boldsymbol{b} = (b_1, b_2, …, b_K)$, the values of r are given by $r \equiv r(\boldsymbol{n}) = C/(\boldsymbol{nb} + b_k)$. The bandwidth of all in-service calls is also compressed by the same factor $r(\boldsymbol{n})$ and becomes equal to $b_i^{comp} = \frac{C}{j'} b_i$ for i = 1,…,K. After bandwidth compression, we have $j = C$ and all adaptive calls do not alter their service time. On the other hand, all elastic calls increase their service time so that the product 'service time' by 'bandwidth' remains constant. The minimum bandwidth that a call of service-class k (k =1,…,K) tolerates, is:

$$b_{k,\min}^{comp} = r_{\min} b_k = \frac{C}{T} b_k \tag{2}$$

where $r_{\min} = C/T$ is the minimum proportion of the required peak-bandwidth and is common to all calls.

When an in-service call of service-class k, with bandwidth b_k^{comp}, departs from the system, then the remaining in-service calls of each service-class i (i=1,…,K), expand their bandwidth to b_i^{expan}, in proportion to their peak-bandwidth b_i:

$$b_i^{\exp an} = \min\left(b_i, b_i^{comp} + \frac{b_i}{\sum_{k=1}^{K} n_k b_k} b_k^{comp} \right) \tag{3}$$

B. Determination of link occupancy distribution and various performance metrics

Let $\boldsymbol{\Omega}$ be the system's state space $\boldsymbol{\Omega} = \{ \boldsymbol{n} : 0 \leq \boldsymbol{nb} \leq T \}$. Due to the bandwidth compression/expansion mechanism, we cannot describe the system by a reversible Markov chain (i.e., local balance does not exist between adjacent states of $\boldsymbol{\Omega}$). Therefore, the steady-state distribution $P(\boldsymbol{n})$ does not have a PFS. To derive an approximate but recursive formula for the efficient calculation of the link occupancy distribution, $G(j)$, j=0,1,…,T, we construct a reversible Markov chain that approximates the system by using state multipliers for all states $\boldsymbol{n} \in \boldsymbol{\Omega}$. The local balance equations between the adjacent states $\boldsymbol{n}_k^{-1} = (n_1, n_2, …, n_k - 1, …, n_K)$ and $\boldsymbol{n} = (n_1, n_2, …, n_k, …, n_K)$ have the form:

$$P(\boldsymbol{n}_k^{-1})(N_k - n_k + 1)v_k = P(\boldsymbol{n})\phi_k(\boldsymbol{n})\mu_k n_k, \; k \in K_e \tag{4}$$

$$P(\boldsymbol{n}_k^{-1})(N_k - n_k + 1)v_k = P(\boldsymbol{n})\phi_k(\boldsymbol{n})\mu_k n_k, \; k \in K_a \tag{5}$$

where $\phi_k(\boldsymbol{n})$ is a state multiplier and is defined as:

$$\phi_k(\boldsymbol{n}) = \begin{cases} 1 & , \; when \; \boldsymbol{nb} \leq C \; and \; \boldsymbol{n} \in \boldsymbol{\Omega} \\ \dfrac{x(\boldsymbol{n}_k^{-1})}{x(\boldsymbol{n})}, & when \; C < \boldsymbol{nb} \leq T \; and \; \boldsymbol{n} \in \boldsymbol{\Omega} \\ 0 & , \; otherwise \end{cases} \tag{6}$$

and

$$x(\boldsymbol{n}) = \begin{cases} 1 & , \; when \;\; \boldsymbol{nb} \leq C, \; \boldsymbol{n} \in \boldsymbol{\Omega} \\ \dfrac{1}{C}\left(\sum_{k \in K_e} n_k b_k x(\boldsymbol{n}_k^{-1}) + r(\boldsymbol{n}) \sum_{k \in K_a} n_k b_k x(\boldsymbol{n}_k^{-1}) \right) & \\ & , \; when \;\; C < \boldsymbol{nb} \leq T, \; \boldsymbol{n} \in \boldsymbol{\Omega} \\ 0 & , \; otherwise \end{cases} \tag{7}$$

where $r(\boldsymbol{n})=C/\boldsymbol{nb}$.

When $C < \boldsymbol{nb} \le T$ and $\boldsymbol{n} \in \boldsymbol{\Omega}$ the values of bandwidth of all in-service calls are compressed by a factor $\phi_k(\boldsymbol{n})$ so that:

$$\sum_{k \in K_e} n_k b_k^{comp} + \sum_{k \in K_a} n_k b_k^{comp} = C \quad (8)$$

To derive (7), we keep the product 'service time' by 'bandwidth' of service-class k calls (elastic or adaptive) in state $\boldsymbol{n}$ of the irreversible Markov chain equal to the corresponding product in the same state $\boldsymbol{n}$ of the reversible Markov chain. This means that:

$$\frac{b_k r(\boldsymbol{n})}{\mu_k r(\boldsymbol{n})} = \frac{b_k^{comp}}{\mu_k \phi_k(\boldsymbol{n})} \Rightarrow b_k^{comp} = b_k \phi_k(\boldsymbol{n}),\ k \in K_e \quad (9)$$

and

$$\frac{b_k r(\boldsymbol{n})}{\mu_k} = \frac{b_k^{comp}}{\mu_k \phi_k(\boldsymbol{n})} \Rightarrow b_k^{comp} = b_k \phi_k(\boldsymbol{n}) r(\boldsymbol{n}),\ k \in K_a \quad (10)$$

Equation (7) results by substituting (9), (10) and (6), into (8).

In order to prove a recursive formula for the calculation of $G(j)$'s, we consider two cases: i) states where $0 \le j \le C$ and ii) states where $C < j \le T$.

When $0 \le j \le C$, then $\phi_k(\boldsymbol{n})=1$ and based on (4) and (5), it is proved that [14]:

$$G(j) = \begin{cases} 1 & \text{for } j = 0 \\ \dfrac{1}{min(j,C)} \sum_{k \in K} (N_k - n_k + 1)\alpha_k b_k G(j - b_k) & \text{for } j = 1,...,T \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

where: $\alpha_k = v_k/\mu_k$ is the offered traffic-load (in erl) per idle source of service-class k.

When $C < j \le T$, we multiply both sides of (4) by b_k^{comp} and sum over k=1,…,K_e to have:

$$\sum_{k \in K_e} (N_k - n_k + 1) a_k b_k^{comp} P(\boldsymbol{n}_k^{-1}) = P(\boldsymbol{n}) \sum_{k \in K_e} n_k b_k^{comp} \phi_k(\boldsymbol{n}) \quad (12)$$

Based on (6) and (9), (12) is written as:

$$x(\boldsymbol{n}) \sum_{k \in K_e} (N_k - n_k + 1) a_k b_k P(\boldsymbol{n}_k^{-1}) = P(\boldsymbol{n}) \sum_{k \in K_e} x(\boldsymbol{n}_k^{-1}) n_k b_k \quad (13)$$

We continue by multiplying both sides of (5) by b_k^{comp} and sum over k=1,…,K_a to have:

$$\sum_{k \in K_a} (N_k - n_k + 1) a_k b_k^{comp} P(\boldsymbol{n}_k^{-1}) = P(\boldsymbol{n}) \sum_{k \in K_a} n_k b_k^{comp} \phi_k(\boldsymbol{n}) \quad (14)$$

Based on (6) and (10) and since $r(\boldsymbol{n})$ = C/j, (14) can be written as:

$$x(\boldsymbol{n}) \frac{C}{j} \sum_{k \in K_a} (N_k - n_k + 1) a_k b_k P(\boldsymbol{n}_k^{-1}) = P(\boldsymbol{n}) \frac{C}{j} \sum_{k \in K_a} x(\boldsymbol{n}_k^{-1}) n_k b_k \quad (15)$$

Adding (13) and (15) we have:

$$x(\boldsymbol{n}) \left(\sum_{k \in K_e} (N_k - n_k + 1) a_k b_k P(\boldsymbol{n}_k^{-1}) + \frac{C}{j} \sum_{k \in K_a} (N_k - n_k + 1) a_k b_k P(\boldsymbol{n}_k^{-1}) \right)$$
$$= P(\boldsymbol{n}) \left(\sum_{k \in K_e} x(\boldsymbol{n}_k^{-1}) n_k b_k + \frac{C}{j} \sum_{k \in K_a} x(\boldsymbol{n}_k^{-1}) n_k b_k \right) \quad (16)$$

Due to (7), (16) can be written as:

$$\sum_{k \in K_e} (N_k - n_k + 1) a_k b_k P(\boldsymbol{n}_k^{-1}) + \frac{C}{j} \sum_{k \in K_a} (N_k - n_k + 1) a_k b_k P(\boldsymbol{n}_k^{-1}) = CP(\boldsymbol{n}) \quad (17)$$

To introduce the link occupancy distribution $G(j)$ in (17), let $\boldsymbol{\Omega}_j = \{\boldsymbol{n} \in \boldsymbol{\Omega} : \boldsymbol{nb} = j\}$ be the state space where exactly j b.u. are occupied. Then, since $\sum_{\boldsymbol{n} \in \boldsymbol{\Omega}_j} P(\boldsymbol{n}) = G(j)$, summing both sides of (17) over $\boldsymbol{\Omega}_j$ we obtain:

$$\sum_{\boldsymbol{n} \in \boldsymbol{\Omega}_j} \sum_{k \in K_e} (N_k - n_k + 1) a_k b_k P(\boldsymbol{n}_k^{-1}) +$$
$$\frac{C}{j} \sum_{\boldsymbol{n} \in \boldsymbol{\Omega}_j} \sum_{k \in K_a} (N_k - n_k + 1) a_k b_k P(\boldsymbol{n}_k^{-1}) = CG(j) \quad (18)$$

Interchanging the order of summations in (18) and assuming that each state has a unique occupancy j we have:

$$\sum_{k \in K_e} (N_k - n_k + 1) a_k b_k \sum_{\boldsymbol{n} \in \boldsymbol{\Omega}_j} P(\boldsymbol{n}_k^{-1}) +$$
$$\frac{C}{j} \sum_{k \in K_a} (N_k - n_k + 1) a_k b_k \sum_{\boldsymbol{n} \in \boldsymbol{\Omega}_j} P(\boldsymbol{n}_k^{-1}) = CG(j) \quad (19)$$

or

$$\sum_{k \in K_e} (N_k - n_k + 1) a_k b_k G(j - b_k) +$$
$$\frac{C}{j} \sum_{k \in K_a} (N_k - n_k + 1) a_k b_k G(j - b_k) = CG(j) \quad (20)$$

The combination of (11) and (20) gives the approximate recursive formula of $G(j)$'s, when $1 \le j \le T$:

$$G(j)=\begin{cases}1 & \text{for } \ j=0\\ \dfrac{1}{\min(j,C)}\sum_{k\in K_e}(N_k-n_k+1)\alpha_k b_k G(j-b_k) & \\ +\dfrac{1}{j}\sum_{k\in K_a}(N_k-n_k+1)\alpha_k b_k G(j-b_k) & \text{for } j=1,...,T\\ 0 & \text{for } \ j<0\end{cases} \quad (21)$$

When $N_k \to \infty$ for k=1,…,K then the call arrival process is Poisson and the formula of $G(j)$'s is [2]:

$$G(j)=\begin{cases}1 & \text{for } \ j=0\\ \dfrac{1}{\min(j,C)}\sum_{k\in K_e}\alpha_k b_k G(j-b_k)+ & \\ \dfrac{1}{j}\sum_{k\in K_a}\alpha_k b_k G(j-b_k) & \text{for } \ j=1,...,T\\ 0 & \text{for } \ j<0\end{cases} \quad (22)$$

where $\alpha_k=\lambda_k/\mu_k$ (in erl) and λ_k is the arrival rate of calls of service-class k.

The determination of $G(j)$'s in (21) requires the value of n_k which is unknown. In other finite multirate loss models (e.g., [14], [15]) there exist calculation methods for the determination of n_k in each state j through the use of 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, we avoid such methods and approximate n_k in state j, $n_k(j)$, as the mean number of service-class k calls in state j, $y_k(j)$, when Poisson arrivals are considered, i.e., $n_k(j)\approx y_k(j)$. Such approximations are common in the literature and induce little error (e.g., [16],[17]). The values of $y_k(j)$ are given by (23), (24) in the case of elastic and adaptive service-classes, respectively [2]:

$$\begin{aligned}y_k(j)G(j)&=\frac{1}{\min(C,j)}a_k b_k G(j-b_k)\left(y_k(j-b_k)+1\right)\\ &+\frac{1}{\min(C,j)}\sum_{\substack{i=1\\ i\neq k}}^{K_e}a_i b_i G(j-b_i)y_k(j-b_i)\\ &+\frac{1}{j}\sum_{i=1}^{K_a}a_i b_i G(j-b_i)y_k(j-b_i)\end{aligned} \quad (23)$$

$$\begin{aligned}y_k(j)G(j)&=\frac{1}{j}a_k b_k G(j-b_k)\left(y_k(j-b_k)+1\right)\\ &+\frac{1}{j}\sum_{\substack{i=1\\ i\neq k}}^{K_a}a_i b_i G(j-b_i)y_k(j-b_i)\\ &+\frac{1}{\min(C,j)}\sum_{i=1}^{K_e}a_i b_i G(j-b_i)y_k(j-b_i)\end{aligned} \quad (24)$$

where the values of $G(j)$'s are determined by (22).

Having determined $G(j)$'s according to (21), we calculate the following performance measures:

1) The TC probabilities of service-class k, denoted as P_{b_k}, which is the probability that at least T-b_k+1 b.u are occupied:

$$P_{b_k}=\sum_{j=T-b_k+1}^{T}G^{-1}G(j) \quad (25)$$

where: $G=\sum_{j=0}^{T}G(j)$ is a normalization constant.

TC probabilities are determined by the proportion of time the system is congested.

2) The CC probabilities of service-class k, denoted as C_{b_k}, which is the probability that a new service-class k call is blocked and lost:

$$C_{b_k}=\sum_{j=T-b_k+1}^{T}G^{-1}G(j) \quad (26)$$

where $G(j)$'s are determined for a system with N_k - 1 traffic sources.

CC probabilities are determined by the proportion of arriving calls that find the system congested.

3) The link utilization, denoted as U:

$$U=\sum_{j=1}^{C}jG^{-1}G(j)+\sum_{j=C+1}^{T}CG^{-1}G(j) \quad (27)$$

III. EVALUATION

In this section, we present an application example and compare the analytical results of the TC probabilities, CC probabilities and link utilization obtained by the proposed model and the E-EMLM. The corresponding simulation results, presented for the proposed model only, are mean values of 6 runs. Simulation is based on Simscript II.5 [18].

We consider a single link of capacity C = 90 b.u. that accommodates calls of three service-classes. The first two service-classes are elastic, while the third service-class is adaptive. The traffic characteristics of each service-class are:

1st service-class: N_1=200, v_1 = 0.10, b_1 = 1 b.u.

2nd service-class: N_2=200, v_2 = 0.04, b_2 = 4 b.u.

3rd service-class: N_3=200, v_3 = 0.01, b_3 = 6 b.u.

In the case of the E-EMLM the corresponding Poisson traffic loads are: α_1= 20 erl, α_2= 8 erl and α_3= 2 erl.

We also consider two values of T: a) T = 90 b.u. , where no bandwidth compression takes place and b) T = 100 b.u., where bandwidth compression takes place and $r_{\min}$ = C/T=0.9. In the x-axis of all figures, v_1 and v_2 increase in steps of 0.01 and 0.005 erl, respectively while v_3 remains constant. So in Point 1 we have (v_1, v_2, v_3) = (0.10, 0.04, 0.01), while in Point 6 (v_1, v_2, v_3) = (0.15, 0.065, 0.01). In

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the case of the E-EMLM the corresponding Poisson traffic loads in Point 1 and Point 8 are (α_1, α_2, α_3)= (20, 8, 2) and (α_1, α_2, α_3)= (30, 13, 2), respectively.

In Figs. 1-3, we present the analytical and the simulation TC probabilities of the three service-classes while in Figs. 4-6, we present the corresponding analytical and simulation CC probabilities. In all cases, both *T*=90 and *T*=100 b.u. are considered. Note that the term *N*=inf. in all figures refers to the E-EMLM where the number of traffic sources is infinite for each service-class. All figures show that: i) analytical and simulation results for both TC and CC probabilities are very close, ii) the application of the compression/expansion mechanism reduces congestion probabilities compared to those obtained when *C*=*T*=90 b.u. and iii) the results obtained by the E-EMLM fail to approximate the corresponding results obtained by the proposed model (quasi-random traffic model). Finally, in Fig. 7, we present the analytical and simulation results of the link utilization (in b.u.). It is clear, that the application of the bandwidth compression/expansion mechanism increases link utilization since it decreases CC probabilities.

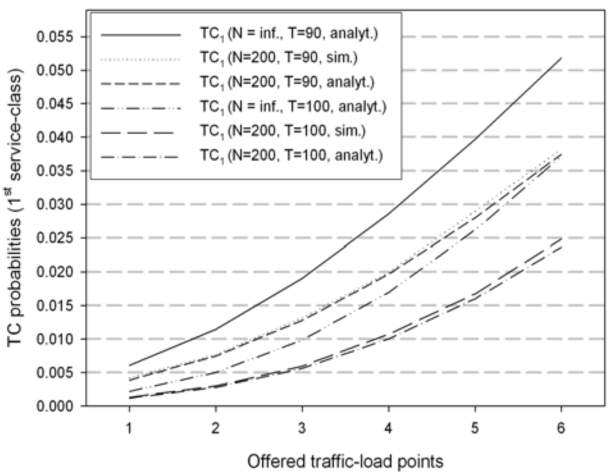

Figure 1. TC probabilities of the 1st service-class.

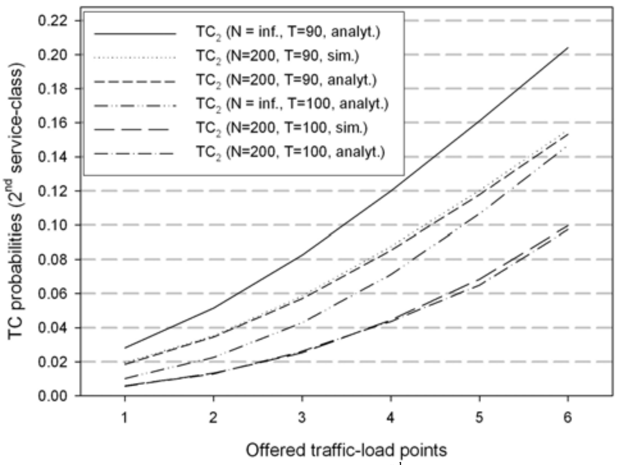

Figure 2. TC probabilities of the 2nd service-class.

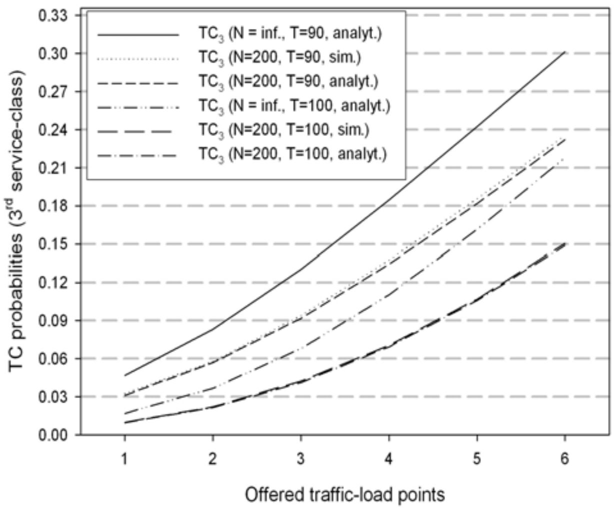

Figure 3. TC probabilities of the 3rd service-class.

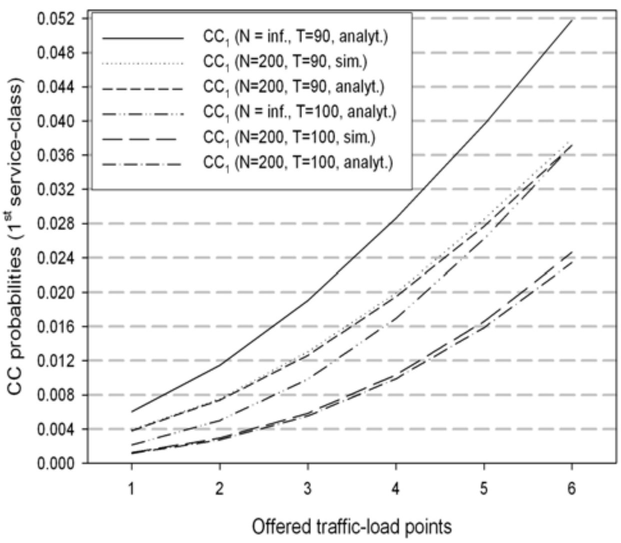

Figure 4. CC probabilities of the 1st service-class.

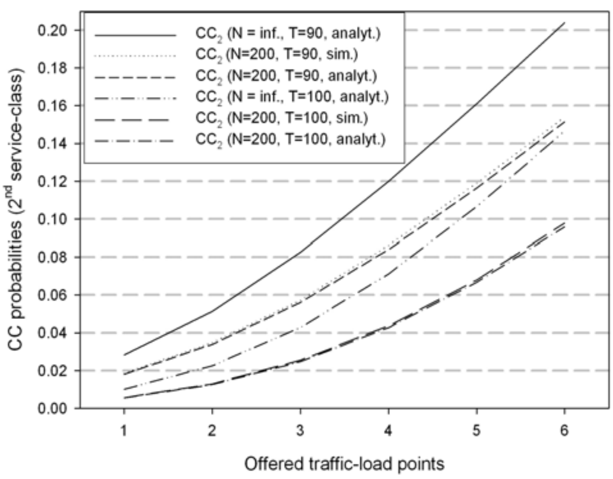

Figure 5. CC probabilities of the 2nd service-class.

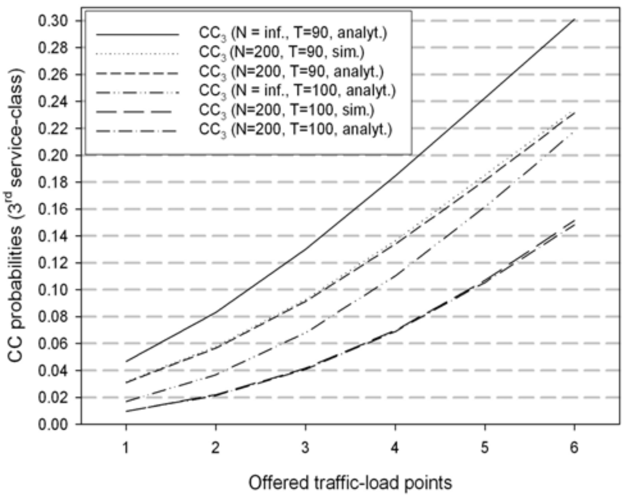

Figure 6. CC probabilities of the 3rd service-class.

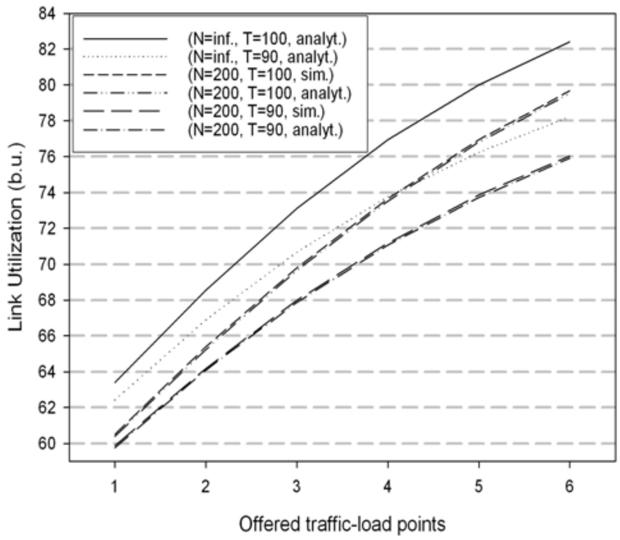

Figure 7. Link utilization (in b.u.)

IV. CONCLUSION

We propose an analytical model for the call-level performance assessment of telecom networks, when elastic and/or adaptive calls of different service-classes come from finite traffic-sources and compete for the available bandwidth of a single link with certain capacity. Due to the existence of the bandwidth compression/expansion mechanism, the proposed model does not have a product form solution. Therefore, we propose approximate but recursive formulas for the calculation of the most important performance measures, namely TC and CC probabilities and link utilization. Simulation results verify the analytical results and prove the accuracy and the consistency of the proposed model. Furthermore, the comparison of the results obtained by the proposed model and the E-EMLM shows the necessity of the proposed model, since the E-EMLM fails to approximate the case of quasi-random traffic. Potential applications of the proposed model are in the environment of wireless networks that support elastic and adaptive traffic.

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