

GENERALISED ANALYSIS OF BUFFER MANAGEMENT IN HETEROGENEOUS MULTI-SERVICE MOBILE NETWORKS

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Abstract: Efficient and adaptive buffer management will play crucial role in the future integrated mobile network (e.g., 4th Generation). One of the main features of the future mobile networks will be their capability of providing different levels of quality of service to the different types of services. Some of these services will be delay and delay variation sensitive such as real-time voice and video. Others will be loss sensitive such as data transfer. But the most challenging will be the sort of multimedia traffic that owns both types of sensitivity. Another source of difficulty stems from the heterogeneous wireless air interface technologies that will act as border nodes to the network providing different traffic streams with different data rates and QoS requirements (e.g, WLAN provides data rates of 11Mbbps while UMTS can only provide 384Kbps). Although improved call admission control algorithms on the border of the network will provide a sort of protection from extensive traffic over the network, however, they will only operate on mean traffic volumes and will not cope with the variability of actual instantaneous traffic entering the network. Furthermore, as the core part of the mobile network will be packet switched based on IP, the QoS can only be maintained through efficient buffer management at the border and inside the network. This paper proposes and analytically evaluates a buffer management scheme that is based on multi-level priority and Partial Buffer Sharing (PBS) policy for all buffers at the border and inside the wireless network. The analytical model is based on the G/G/1/N censored queue with single server and R ($R \geq 2$) priority classes under the Head of Line (HOL) service rule for the PBS scheme. The traffic is modelled using the Generalised Exponential distribution. The paper presents an analytical solution based on the approximation using the Maximum Entropy (ME) principle. The numerical results show the capability of the space prioritised buffer management scheme to provide higher QoS for the higher priority service classes.

Keywords

UMTS networks, performance evaluation, maximum entropy (ME) principle, generalised exponential (GE) distribution, head-of-line (HOL) discipline, partial buffer sharing (PBS) rule.

1 INTRODUCTION

The Third Generation (3G) mobile networks [1] are under deployment in many regions in the world. In Europe, the Universal Mobile Telecommunications System (UMTS) has been implemented by almost every major mobile network operator offering new mostly multimedia based services. At the moment, the volume of data traffic in mobile networks is still moderate but it is obvious that as more and more customers join the new opportunities offered by 3G, the volume and the nature of the traffic at both the border and inside the mobile network will be very different. Furthermore, many of the new services will require more strict quality of service (QoS) guarantees than the simple data transmission, mainly

regarding packet loss, delay and delay variation. Therefore, it is important to implement suitable algorithms to provide prioritization between services and to guarantee preferable treatment to the packets belonging to the higher priority services. This leads to a traffic with Differentiated Services (DS).

Finite buffer queues with service and space priorities are of great importance towards effective congestion control and quality of service (QoS) protection in high speed telecommunication networks. Many queueing systems with priorities have been explored by Cohen [3] and various applications of the analytical results of priority queues to data communication systems are surveyed by de Moraes [4]. A stable infinite capacity G/G/1 queue with a single

server and priority classes under either Preemptive-Resume (PR) or Head-of-the-Line (HOL) scheduling disciplines has been analysed in [5], by applying the method of entropy maximisation (MEM). MEM has also been used in [6] to study a stable single class G/G/1/N censored queue with a single server and First-Come-First-Served (FCFS) scheduling discipline.

Priority mechanisms include time priorities and space priorities. Time priority mechanisms such as HOL (e.g., [7]) and PR (e.g., [8]), take into account that some services may tolerate longer delays than others (e.g., data versus voice) and deal with the order with which jobs are transmitted. Space priorities control the allocation of buffer space to arriving jobs at an input or output port queue of a network switch. Implicitly, they provide several grades of service through the selective discarding of low priority jobs. This type of priority mechanism exploits the fact that certain jobs generated by traffic sources are less important than others and may, therefore, be discarded without significantly affecting the QoS constraints. Two main mechanisms for space priorities are push-out and partial buffer sharing (PBS). Li and Yin et al (c.f., [9], [10]) applied PBS and selective packet discarding for the overload control of packet voice systems modelled by M/PH/1/N and PH/M/1/N queues. An M/M/G/1/N queueing system employing PBS scheme was studied by Kroner (c.f., [11]).

A stable G/G/1/N censored queue with a single server, finite capacity and priority classes under complex buffer management schemes is an important building block in the performance of communication networks. The analysis of such queue is very difficult to tackle using the classical queueing theory. To the authors' knowledge, no exact or approximate closed-form solutions for a stable G/G/1/N censored queue with space and service priorities have appeared in the literature. This paper presents further advances of MEM towards the approximate analysis of a stable G/G/1/N censored queue with a single server, and, $R (R \geq 2)$ priority classes under HOL service rule for PBS scheme.

Entropy maximisation and the generating function approach [12] are applied to characterise recursive expressions for state probabilities and basic performance measures for a single server finite capacity GE/GE/1/N queue with (i) $R (R \geq 2)$ distinct priority classes under head-of-line (HOL) scheduling rule (ii) partial buffer sharing (PBS) management scheme corresponding to a sequence of buffer thresh-

olds $\{\mathbf{N} = (N_1, N_2, \dots, N_R), 0 < N_i \leq N_{i-1}, i = 2, \dots, R\}$ and (iii) compound Poisson arrival processes (CCPs) with geometrically distributed batches and generalised exponential (GE) service times, subject to suitable GE-type queueing theoretic mean value constraints. stable G/G/1/N censored queue with space and service priorities is characterised in Section 2. Marginal performance distributions together with the blocking probabilities and the Lagrangian coefficients are presented in Section 3. Numerical validation results against simulation, involving Generalised Exponential (GE) interarrival and service time distributions, are included in Section 4. Section 5 includes conclusions and remarks for future work.

Remarks

- *The Principle of ME*

The principle of ME [13, 14] provides a self-consistent method of inference for characterising an unknown but true probability distribution, subject to known (or known to exist) mean value constraints. The ME solution can be expressed in terms of a normalising constant and a product of Lagrangian coefficients corresponding to the constraints. In an information theoretic context [13], the ME solution corresponds to the maximum disorder of system states and, thus, is considered to be the least biased distribution estimate of all solutions that satisfy the system's constraints. In sampling terms, it has been shown [14] that, given the imposed constraints, the ME solution can be experimentally realised in overwhelmingly more ways than any other distribution. More details on entropy maximisation and its applications can be found in [15].

- *The GE Distribution*

The GE distribution is an interevent-time distribution of the form

$$F(t) = P(W \leq t) = 1 - \tau e^{-\sigma t}, t \geq 0, \quad (1)$$

$$\tau = 2/(C^2 + 1), \quad (2)$$

$$\sigma = \tau\nu, \quad (3)$$

where W is a mixed-type random variable (rv) of the interevent-time, whilst $(1/\nu, C^2)$ are the mean and squared coefficient of variation (SCV) of rv W . The GE distribution is versatile, possessing pseudo-memoryless properties which makes the solution of many GE-type queueing systems and networks analytically tractable [15].

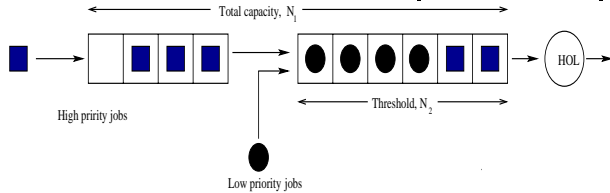
The choice of the GE distribution is further motivated by the fact that measurements of actual

interarrival or service times may be generally limited and so only few parameters can be computed reliably. Typically, only the mean and variance may be relied upon, and thus, a choice of a distribution which implies least bias (i.e., introduction of arbitrary and, therefore, false assumptions) is that of GE-type distribution. For example, in the context of ATM networks, this model is particularly applicable in cases of traffic with low level of correlation or where smoothing schemes are introduced at the adaptation level (e.g., for a stored video source) with the objective of minimising or even eliminating the problem of traffic correlation [16].

- *The PBS Management Schemes*

The PBS management scheme, on the other hand, works by setting a descending sequence of thresholds N_i ($N_i > 0$, $i = 1, 2, \dots, R$) corresponding to R priority classes of a single server queue with finite capacity N_1 . Different job loss and QoS requirements under various load conditions can be met by adjusting the threshold values. The highest priority jobs of class 1 can join the queue simply if there is space. However, lower priority jobs of class i ($i = 2, \dots, R$) can only join the queue if the total number of jobs in the queue is less than a threshold value N_i ($N_i \leq N_{i-1}$). Once the number of jobs waiting for service reaches N_i , all lower priority jobs of class k ($k = i+1, \dots, R$) will be lost on arrival but higher priority jobs of class ℓ ($\ell = 1, \dots, i-1$) will continue to join the queue until it reaches threshold value, N_ℓ ($\ell = 1, \dots, i-1$) for PBS with two HOL job classes, respectively).

The employment of single server finite capacity queues under a PBS scheme and applications into the performance evaluation of high speed networks can be seen in [17, 18, 19, 20].



The PBS management scheme with two HOL job classes

2 ANALYSIS OF GE/GE/1/N PRIORITY QUEUE

Consider a single server finite capacity GE/GE/1/N queue at equilibrium with R ($R > 1$) distinct priority classes of jobs (indexed from 1 to R in descending order of priority) such that

- the total buffer capacity is N_1 ($N_1 > 0$) and the vector \mathbf{N} is specified either by N_1 for a CBS scheme or by a sequence of thresholds $\{(N_1, N_2, \dots, N_R), 0 < N_i \leq N_{i-1}, i = 2, \dots, R\}$ for a PBS scheme.
- the interarrival and service times per class are distributed according to a GE distribution under HOL service rule in conjunction with PBS buffer management scheme.

Notation

For each class i ($i = 1, 2, \dots, R$), let λ_i be the mean arrival rate, $C_{a_i}^2$ be the interarrival time SCV, μ_i be the mean service rate and $C_{s_i}^2$ be the service time SCV.

Focusing on a stable GE/GE/1/N queue, let at any given time

n_i ($0 \leq n_i \leq N_i$) be the number of class i ($i = 1, 2, \dots, R$) jobs in the queue (waiting and/or receiving service)

$\mathbf{S} = (n_1, n_2, \dots, n_R, \omega)$ be a joint queue state, where ω ($1 \leq \omega \leq R$) denotes the class of the current job in service and $\sum_{i=1}^R n_i \leq N_1$ (n.b., for an idle queue $\mathbf{S} \equiv \mathbf{0}$ with $\omega = 0$)

\mathbf{Q} be the set of all feasible states \mathbf{S}

$\mathbf{n} = (n_1, n_2, \dots, n_R)$ be an aggregate joint queue state (n.b., $\mathbf{0} = (0, \dots, 0)$)

$\mathbf{\Omega}$ be the set of all feasible states \mathbf{n}

Remarks

- The arrival process for each class i ($i = 1, 2, \dots, R$) is assumed to be censored i.e., a job of class i will be lost if on arrival finds N_i ($i = 1, 2, \dots, R$) jobs at the queue.

2.1 A Universal Maximum Entropy Solution

The form the state probability distribution, $P(\mathbf{n})$, $\mathbf{n} \in \mathbf{\Omega}$, can be characterised by maximising the entropy functional $H(\mathbf{n}) = -\sum_s P(\mathbf{n}) \log P(\mathbf{n})$, subject to prior information expressed in terms of the normalisation and for each class i ($i = 1, 2, \dots, R$) the marginal constraints of server utilisation, busy state probabilities, mean queue length and full buffer state probabilities satisfying the flow balance equations, namely

$$\lambda_i(1 - \pi_i) = \mu_i U_i, \quad i = 1, 2, \dots, R; \quad (4)$$

where π_i is the blocking probability that an arriving job of class i finds N_i ($i = 1, \dots, R$) jobs in the queue (waiting or receiving service). The choice of aforementioned mean value constraints is based on the type of constraints used for the ME analysis of a stable multiple class queues with or without priorities (c.f., [15, 21, 22, 23]). Note that if additional constraints are used, it is no longer feasible to capture a computationally efficient ME solution in closed-form. By employing Lagrange's method of undetermined multipliers, the ME solution is expressed by

$$P(\mathbf{S}) = \frac{1}{Z} \prod_{i=1}^R g_i^{s_i(\mathbf{S})} \xi_i^{h_i(\mathbf{S})} x_i^{n_i(\mathbf{S})} y_i^{f_i(\mathbf{S})}, \forall \mathbf{S} \in \mathbf{Q}; \quad (5)$$

where $Z = 1/P(0)$, is the normalising constant, $\{g_i, \xi_i, x_i, y_i, i = 1, 2, \dots, R\}$ are the Lagrangian coefficients corresponding to aforementioned constraints per class, respectively and $n_i(\mathbf{S}), s_i(\mathbf{S}), h_i(\mathbf{S})$ and $f_i(\mathbf{S})$ are suitable auxiliary function defined by:

$$\begin{aligned} n_i(\mathbf{S}) &= \text{the number of class } i \text{ jobs present in state } \mathbf{S}, \\ s_i(\mathbf{S}) &= \begin{cases} 1, & \text{if } \omega = i, \\ 0, & \text{otherwise.} \end{cases} \\ h_i(\mathbf{S}) &= \begin{cases} 1, & \text{if } n_i(\mathbf{S}) > 0, \\ 0, & \text{otherwise.} \end{cases} \\ f_i(\mathbf{S}) &= \begin{cases} 1, & \text{if } \sum_{i=1}^R n_i(\mathbf{S}) = N_i \text{ \& } \omega = i, \\ 0, & \text{otherwise.} \end{cases} \end{aligned}$$

An efficient computational implementation of the ME solution (5) requires the prior estimation of the Lagrangian coefficients. This can be achieved by making GE-type buffer size invariance assumptions with regard to Lagrangian coefficients $\{g_i, \xi_i, x_i, i = 1, 2, \dots, R\}$ together with asymptotic connections to an infinite capacity GE/GE/1 queue (c.f., [15]). The Lagrangian coefficients y_i can be calculated using the flow balance condition.

Aggregating (5) over all feasible states $\mathbf{S} \in \mathbf{Q}$, and after some manipulation, the joint aggregate ME queue length distribution $\{P(\mathbf{n}), \mathbf{n} \in \Omega\}$ is given by:

$$P(\mathbf{0}) = \frac{1}{Z}. \quad (6)$$

$$P(\mathbf{n}) = \frac{1}{Z} \left(\prod_{i=1}^R x_i^{n_i} \xi_i^{h_i(\mathbf{n})} \right) \left(\sum_{j=1 \wedge n_j > 0}^R g_j y_j^{f_i(\mathbf{n})} \right) \quad (7)$$

$\forall \mathbf{n} \in \Omega - \{\mathbf{0}\}$; where $h_i(\mathbf{n}) = 1$, if $n_i > 0$, or 0 otherwise and $f_i(\mathbf{n}) = 1$, if $\sum_{j=1}^R n_j = N_i$, or 0, otherwise, for $i = 1, 2, \dots, R$.

3 PERFORMANCE DISTRIBUTIONS

Taking advantage of the ME product-form solution (6)-(7) and applying the generating function approach [12], recursive expressions for marginal utilisations U_i , aggregate state probabilities $\{P(n), n = 0, \dots, N_1\}$, marginal state probabilities $\{P_i(n_i), n_i = 0, 1, \dots, N_i\}$ and marginal mean queue lengths L_i for $i = 1, \dots, R$ can be obtained.

3.1 Marginal Utilisations

It can be observed that the marginal utilisations $\{U_i, i = 1, \dots, R\}$ are clearly defined by $U_i = \sum_{\mathbf{S} \in \mathbf{Q}} s_i(\mathbf{S}) P(\mathbf{S})$ and after some manipulation, they take the following universal form, namely

$$U_i = \frac{1}{Z} g_i \xi_i x_i \left(\sum_{v=1}^{N_1} y_i^{\gamma(v)} C^{(i)}(v-1) \right); \quad (8)$$

where Z is the normalising constant and $\gamma(v) = 1$, if $v = N_i$ or 0, otherwise. $C^{(i)}(v)$ can be calculated recursively using the following expressions:

$$\begin{aligned} C^{(i)}(v) &= (1 - \xi_i) x_i C^{(i)}(v-1) - x_i^{N_i} C(v - N_i) \\ &\quad + C(v) + x_i^{N_i+1} \xi_i C^{(i)}(v - N_i - 1), \quad (9) \end{aligned}$$

for $v = 1, 2, \dots, N_1 - 1$; $i = 1, 2, \dots, R$ with initial conditions $C^{(i)}(v) = 0$ if $v < 0$ and 1 if $v = 0$; where $C(v) = C_R(v)$ and

$$\begin{aligned} C_r(v) &= x_r C_r(v-1) - (1 - \xi_r) x_r C_{r-1}(v-1) + \\ &\quad C_{r-1}(v) - \xi_r x_r^{N_r+1} C_{r-1}(v - N_r - 1) \quad (10) \end{aligned}$$

$r = 1, 2, \dots, R$ with initial conditions $C_r(v) = 0$ if $v < 0$, 1 if $v = 1$ and $\xi_1 x_1^v$ if $v > 0$.

3.2 Marginal State Probabilities

Aggregating ME solution $\{P(\mathbf{S}), \mathbf{S} \in \mathbf{Q}\}$ and defining an appropriate z-transform [12], after some manipulation, the following recursive expressions for the marginal probabilities can be obtained:

$$\begin{aligned} P_i(0) &= 1 - \theta_i \\ &= \frac{1}{Z} \left(1 + \sum_{j=1 \wedge j \neq i}^R g_j \xi_j x_j \left(\sum_{v=0}^{N_j-1} C_i^{(j)}(v) y_j^{\delta(v)} \right) \right), \\ P_i(n) &= \frac{1}{Z} \xi_i x_i^n \left(\sum_{j=1}^R g_j E_j \left(\sum_{k=1 \wedge k \neq i}^R \sum_{v=0}^{\min(N_k, N_1-n)-F} C_i^{(j)}(v) y_j^{\delta(v)} \right) \right), \quad (11) \end{aligned}$$

where $E_j = \xi_j x_j$ if $j \neq i$ or 1 ow, $F = 1$ if $j \neq i$ or 0 ow. The coefficients $\{C_i^{(j)}(v), v = 0, 1, \dots, N_1 -$

$1, (i, j) \in [1, R]$ can be determined by the following recursive formulae:

$$C_i^{(j)}(v) = \begin{cases} C^{(j)}(v) - x_i C^{(j)}(v-1) \\ + (1 - \xi_i) x_i C_i^{(j)}(v-1) \\ + \xi_i x_i^{N_i+1} C_i^{(j)}(v - N_i - 1), i \neq j \\ C^{(j)}(v) - x_i C^{(j)}(v-1) + x_i^{N_i} C_i^{(j)}(v - N_i), \\ i = j \end{cases} \quad (12)$$

with initial condition $C_i^{(j)}(v) = 0$ if $v < 0$, or 1, if $v = 0$, where $C^{(j)}(v)$ is determined by (9).

3.3 The Blocking Probability

A universal form for the marginal blocking probabilities $\{\pi_i, i = 1, 2, \dots, R\}$ of a stable multiple class GE/GE/1/N queue can be approximately established, based on GE-type probabilistic arguments, by the following expression:

$$\pi_i = \frac{1}{Z} \left(\sum_{v=0}^{N_1} (1 - \sigma_i)^{[N_1 - v]^+} \sum_{j=1}^R \delta_i(v) H^{(j)}(v) \right) \quad (13)$$

where $\delta_i(v) = \delta_i$ if $(v = 0)$ or 1 otherwise and

$$H^{(j)}(v) = \begin{cases} g_j \xi_j x_j y_j^{\gamma(v)} C^{(j)}(v), & \forall v > 0; \\ 1, & \text{if } (v = 0 \text{ \& } i \neq j) \\ 0 & \text{otherwise,} \end{cases}$$

$C^{(i)}(n)$ is defined by (9).

4 NUMERICAL RESULTS

This section presents typical numerical experiments in order to illustrate the credibility of the proposed ME solution against simulation. Moreover, it demonstrates the applicability of ME results as simple but cost-effective performance evaluation tools for assessing the effect of external multiple class GPRS traffic at the GE/GE/1/N/HOL queue.

The numerical study focuses on two data packet classes representing typical Internet applications, namely, 12.5 KBytes (class 1, e.g., email) and 62.5 KBytes (class 2, e.g., web browsing) and , respectively. The parameterization also involves mean arrival rates and SCV of inter-arrival and service times. It is assumed that the GPRS partition consists of one frequency providing total capacity of 171.2 Kbps. Without loss of generality, the evaluation study focuses on marginal performance metrics of utilisation, mean response time and mean queue length per class.

The credibility of the proposed ME solution is

demonstrated against simulation (based on QNAP-2 at 95% confidence interval [25]) via typical numerical experiments involving GE-Type queue presented in Figures 1-3. These figures show the performance measures for a censored GE/GE/1/N queue with HoL scheduling disciplines under PBS schemes. It can be observed that under a wide range of input data, the ME solutions are very comparable to those obtained by corresponding simulation models. Furthermore, Fig. 3 shows the effectiveness of using thresholds under PBS scheme in order to provide various grades of services to different classes of jobs.

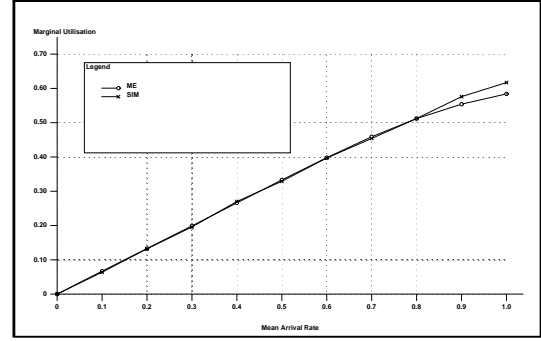


Figure 1: Marginal Utilisations for Class 1 Calls

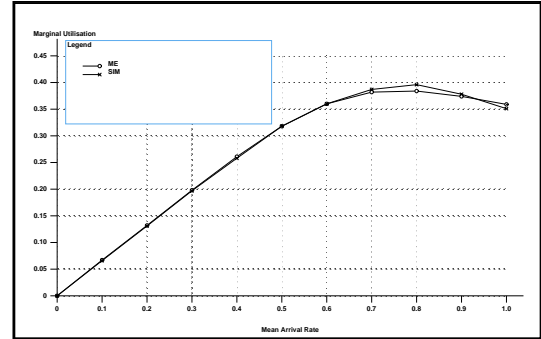


Figure 2: Marginal Utilisations for Class 2 Calls

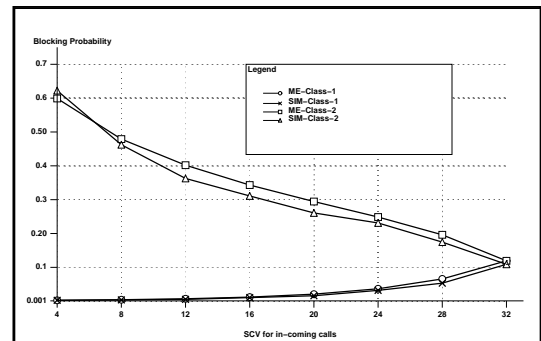


Figure 3: Effect of threshold values on blocking Probabilities

5 CONCLUSIONS

This paper presents an analytical model to evaluate performance of the wireless network where different applications are given preferential treatment in order to provide quality of service. In this context, a G/G/1/N censored queue with single server and R ($R \geq 2$) priority classes under the HOL service rule for the PBS scheme has been analysed using ME principle. Closed form expressions for marginal utilisations, state probabilities and blocking probabilities are presented. Typical numerical experiments show the capability of the PBS management scheme to provide higher QoS for the higher priority service classes.

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Biographies



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