ANALYSIS OF A WIRELESS CELL WITH MULTIPLE SERVICE CLASSES UNDER AN AGGREGATE SHARING SCHEME*

I.AWAN, D.D.KOUVATSOS, K.AL-BEGAIN

Networking and Performance Engineering Research Group
Department of Computing, School of Informatics
University of Bradford, Bradford,
BD7 1DP Bradford, West Yorkshire, England, UK
E-mail : {i.awan, d.d.kouvatsos,k.begain}@bradford.ac.uk,

Abstract:
An analytic framework is devised for the performance modelling and evaluation of a wireless Global System for Mobile telecommunication (GSM) cell with General Packet Radio Service (GPRS) supporting both multiple class voice and data services, respectively, under an aggregate sharing scheme (ASS). The investigation focuses on the study of a proposed GE/GE/c/N/PR/CBS queueing system with c ($\geq$ 1) servers, finite capacity, N ($\geq$ c), generalised exponential (GE) GSM/GPRS interarrival and service times under preemptive resume (PR) priority rule and complete buffer sharing (CBS) scheme. The principle of maximum entropy (ME) is used to characterise new closed form expressions for the state and blocking probabilities, subject to appropriate GE-type queueing theoretic constraints per class. Typical numerical examples are included to validate the ME solution against simulation at 95% confidence intervals and study the effect of external GSM/GPRS bursty traffic upon the performance of the cell.

Key Words: Cellular mobile system, wireless GSM/GPRS cell, aggregate sharing scheme (ASS), performance evaluation, maximum entropy (ME) principle, Generalised Exponential (GE) distribution, preemptive resume (PR) discipline, complete buffer sharing (CBS) rule.

1 Introduction

Earlier performance studies for mobile systems have been based on simulation modelling and numerical solution of Markov models covering different traffic scenarios, mostly at voice call level, with single or multiple service classes. Earlier proposed models are based on resource network management parameters of the Global System for Mobile Telecommunications (GSM) technology, where the capacity of radio interference in the wireless cell is divided into discrete channels and operates in circuit-switched mode (e.g., [1]. Extensions of these models have been made to capture the packet-switched behaviour introduced by the General Packet Radio Service (GPRS) which has been added to GSM to allow data packet communication with higher bit rates than those provided by a single GSM channel (e.g., [2,3]). More recently, Foh et al [4] proposed a single server infinite capacity queue for modelling GPRS in a Markovian environment and applied matrix geometric methods for the evaluation of performance metrics.

Figure 1 shows a simplified block diagram reflecting the most important components of a GSM/GPRS system architecture. The User Equipment (UE) can be generating either GSM Voice and/or GPRS data traffic. Both types of traffic will go through the same air interface or Base Station (BS) but each of them will have its own Um and Gb radio interfaces. The traditional GSM voice call connections will use the original flow path - through the Base Station Controller (BSC) and the Mobile Station Controller (MSC) - to the fixed Public Land Mobile Network (PLMN). On the other hand, the GPRS packet data traffic will use the added Serving GPRS Support Node (SGSN) which in turn will transfer the data -

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*This work is supported by the EU IST Programme's Grant IST-2001-32392

through the Gateway GPRS Support Node (GGSN) - to Public Data Network (PDN). The diagram of Figure 1 can be used, under different call/data handling schemes, to identify the spots where congestion is likely to built up leading to formulation of suitable queueing network models (QNMs).

Simulation is an efficient tool for studying detailed system behaviour but it becomes costly, particularly as the system size increases. Markov models on the other hand provide more flexibility and produce numerical results for many interesting performance measures. Nevertheless, the numerical solution of Markov models may suffer from several drawbacks, such as

- state space explosion limiting the analysis to only small mobile systems, generally consisting of one cell,
- restrictive assumptions of independent Poisson arrival processes for all types of homogeneous and uniformly distributed traffic with exponentially distributed call duration (which, if multiplexed, can be bursty and correlated).

Thus, there is still a great need to apply analytic methodologies for the study of arbitrary QNMs, based on a balanced trade-off between simplified assumptions (to reduce complexity) and actual real life system behaviour, leading to both credible and cost-effective approximations for the performance prediction and optimisation of mobile systems.

This paper devises a robust analytic framework for the performance modelling and evaluation of a wireless GSM/GPRS cell with multiple classes of both voice calls and data packets of traffic under the aggregate sharing scheme (ASS). In this context, a GE/GE/c/N/PR/CBS queueing system is proposed having c (≥ 1) servers, finite capacity, N ($\geq$ c), Compound Poisson arrival processes (CPPs) with geometrically distributed batches (or, equivalently, Generalised Exponential (GE) interarrival times) and GE service times, under preemptive resume (PR) priority rule and complete buffer sharing (CBS) management scheme (i.e., data packets and voice calls can join the queue with preemptive priority to voice calls, as long as there is space). It is assumed that data packets and voice calls have different arrival rates, interarrival and service times squared coefficients of variation (SCVs) and file burst sizes. The principle of maximum entropy (ME) (c.f.,[5]) is used to characterise closed form expressions for the state and blocking probabilities, subject to appropriate GE-type queueing theoretic constraints per class. Focusing on a GE/M/c/N/PR/CBS queue, typical numerical examples are included to validate the ME solution against simulation at 95% confidence intervals and study the effect of external GSM/GPRS bursty traffic upon the performance of the cell.

This paper is organised as follows. Section 2 describes some of the main voice/data capacity handling schemes for wireless GSM/GPRS cells with particular emphasis on the ASS and its related congestion issues and performance implications. Section 3 presents the ME analysis of the GE/GE/c/N/PR/CBS queue. Numerical examples are included in Section 4. Concluding remarks follow in Section 5.

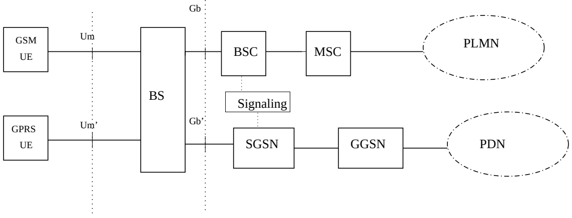

Figure 1: A simplified block diagram of a GSM/GPRS system architecture

2 GSM/GPRS Traffic Handling Schemes

Resources for GPRS traffic can be reserved statically or dynamically whereas a combination of both is possible. Different cell capacity partitioning schemes for handling the transmission of voice calls/data packets can be defined. In such environment, partitions of the available bandwidth may be created for GSM and GPRS traffics but not for individual data services. However, some data calls may be allocated higher priority and, therefore, they can be given higher share of the available bandwidth. Whenever voice and data share bandwidth, voice service is always given the highest priority. Three main GSM/GPRS call/data handling schemes are described below.:

- *Complete partitioning scheme (CPS)* divides the total cell capacity to serve simultaneously GSM and GPRS traffics. As a consequence, the GSM and GPRS systems can be analysed separately.
- *Partial sharing scheme (PSS)* allocates C_{data} channels for data traffic and the remaining $C_{shared} = C_{total} - C_{data}$ channels are shared by voice and data calls with preemptive priority for voice calls.
- *Aggregate sharing scheme (ASS)* enables all available channels to serve at the same time

both voice calls and data packets under a PR rule where voice calls have higher priority over data packets.

Although, CPS will not clearly give the best utilisation for radio resources, it has the advantage of requiring simpler management policy and implementation. Moreover, a definite capacity for GPRS under an efficient Connection Admission Control (CAC) algorithm can guarantees some QoS. Note that the CPS is the limiting case of the PSS under high loads whilst the ASS provides, as an alternative scheme, a cost-effective solution to mobile users/service providers.

The congestion implications of the call/data ASS handling scheme on the performance of a GSM/GPRS wireless cell are discussed below.

2.1 A GSM/GPRS cell with ASS

A GSM/GPRS wireless cell architecture with a ASS related system of queues can be seen in Figure 2. Potential spots of congestion and delays are often attributed to the constraints imposed by BCS dealing with both GSM voice and GPRS data traffics. A number of channels with buffer may be allocated to a single GSM/GPRS partition which can be clearly seen as a multiple server queueing system with finite capacity and multiple class voice calls and data packets. Thus, whilst a common bandwidth management scheme is in operation, any available channel can service either a voice call or a data packet with a PR priority rule for voice calls. On arrival voice calls and data packets will be lost if the queueing system is at full capacity. On the other hand, a data packet will be preempted from service by an arriving voice call when all c channels are busy. A GE/GE/c/N/PR/CBS queue modelling a wireless cell architecture under ASS can be seen in Fig. 3. This model complies with a common bandwidth management protocol and allows the simultaneous access of the GE/GE/c/N/PR/CBS queue by multiple classes of GSM voice calls and GPRS data packets. Note that specific QNMs for wireless GSM/GPRS cells under both CPS and PSS protocols together with some analytic advances have been presented in [6].

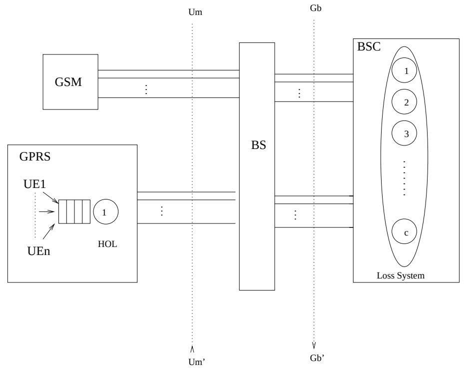

Figure 2: A GSM/GPRS wireless cell architecture with an ASS system of queues

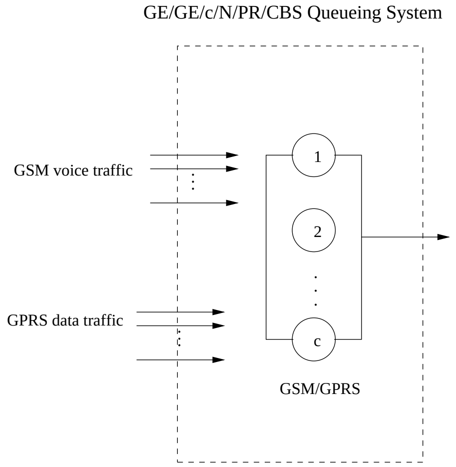

Figure 3: A GE/GE/c/N/PR/CBS queue modelling a wireless cell architecture under ASS

3 Analysis of a GE/GE/c/N/PR/CBS Queue

Consider a finite capacity GE/GE/c/N/PR/CBS queue at equilibrium with $R(R > 1)$ distinct priority classes of jobs (indexed from 1 to R in descending order of priority) under PR service rule and CBS buffer management scheme with a maximum number of servers c (c $\geq$ 1) and a total buffer capacity $N\,(N \geq c)$. It is assumed that the interarrival and service times per class are distributed according to a GE distribution. For each class $i\,(i = 1, 2, \ldots, R)$, let λ_i be the mean arrival rate, C_{ai}^2 be the interarrival time SCV, μ_i be the mean service rate and C_{si}^2 be the service time SCV. Moreover, let at any given time

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

$\mathbf{n} = (n_1, n_2, \ldots, n_R)$ be an aggregate joint queue state (n.b., $\mathbf{0} = (0, \ldots, 0)$), where $\sum_{i=1}^{R} n_i \leq N$.

$\mathbf{Q}$ be the set of all feasible states $\mathbf{n}$, i.e., $\mathbf{Q} = \{\mathbf{n}, n_i \in [0, N];\ i \in [1, R]\}$.

3.1 A ME Product Form Approximation

A product-form of the state probability distribution $\{P(\mathbf{n}), \mathbf{n} \in \mathbf{Q}\}$ can be characterised by maximising the entropy functional $H(P) = -\sum_{\mathbf{n}} P(\mathbf{n}) \log P(\mathbf{n})$ subject to normalisation, utilisation, mean queue length and full buffer state constraints satisfying the flow balance condition

$$\lambda_i(1 - \pi_i) = \mu_i U_i, \tag{1}$$

where U_i is the marginal utilisation of class i, $i = 1, 2, \ldots, R$. By employing Lagrange's method of undetermined multipliers, the ME solution is expressed by

$$P(\mathbf{n}) = \frac{1}{Z} \prod_{i=1}^{R} \left\{ \prod_{k=1}^{c} g_{ik}^{h_{ik}(\mathbf{n})} y_{ik}^{f_{ik}(\mathbf{n})} \right\} x_i^{n_i}, \ \forall \mathbf{n} \in \mathbf{Q} - \{\mathbf{0}\}, \tag{2}$$

where $h_{ik}(\mathbf{n})$ and $f_{ik}(\mathbf{n})$ are auxiliary functions and are defined as:

$$h_{ik}(\mathbf{n}) = \begin{cases} 1 & \text{if } n_i \geq k \text{ and } k \leq c - \sum_{\ell=1}^{i-1} n_i, \\ 0 & \text{otherwise,} \end{cases}$$

$$f_{ik}(\mathbf{n}) = \begin{cases} 1 & \text{if } h_{ik}(\mathbf{n}) = 1 \text{ and } \sum_{i=1}^{R} n_i = N, \\ 0 & \text{otherwise,} \end{cases}$$

Note that ME solution (2) is a generalisation of the ME solutions of Kouvatsos and Tabel Aouel [7,8] for the stable GE/GE/1/PR and GE/GE/c/PR queues, respectively.

3.2 Marginal Utilisations

It can be observed that the marginal utilisations $\{U_i, i = 1, \ldots, R\}$ are clearly defined by $U_i = \sum_{\mathbf{S} \in \mathbf{Q}} h_{ik}(\mathbf{S}) P(\mathbf{S})$ and after some manipulation (c.f., [9]), they take the following universal form, namely

$$U_i = \frac{1}{Z} \sum_{v=1}^{N} \left(\sum_{\mathbf{S} \in A_i^v} x_i^{n_i} \left\{ \prod_{k=1}^{c} g_{ik}^{h_{ik}(\mathbf{S})} y_{ik}^{h_{ik}(\mathbf{S})} \right\} \prod_{j=i+1}^{R} x_j^{n_j} \right), \tag{3}$$

for $i = 1, 2, \ldots, R$, where $\mathbf{A_i^v}$ is the set of all those states of the queue when class-i job is in the service while there are v jobs of class i or higher, while $v \leq N$. From eq. (3), the following expression for the normalising constant Z is derived

$$Z = 1 + \sum_{v=1}^{N} \left(\sum_{\mathbf{n} \in A_i^v} \prod_{i=1}^{R} \left\{ \prod_{k=1}^{c} g_{ik}^{h_{ik}(\mathbf{S})} y_{ik}^{h_{ik}(\mathbf{S})} \right\} x_i^{n_i} \right). \tag{4}$$

3.3 Aggregate State Probabilities

Unconditioning expression (3) over all classes, a universal form for the aggregate utilisation U, can be obtained with aggregate arrival rate λ ($\lambda = \sum_{i=1}^{R} \lambda_i$). Consequently, the aggregate probability distribution $\{P(n), n = 0, 1, \ldots, N\}$ is given by

$$P(n) = \begin{cases} \frac{1}{Z}, \ \text{for } n = 0, \\ \frac{1}{Z} \sum_{\mathbf{n} \in A_i^v} \prod_{i=1}^{R} \left\{ \prod_{k=1}^{c} g_{ik}^{h_{ik}(\mathbf{S})} y_{ik}^{h_{ik}(\mathbf{S})} \right\} x_i^{n_i}, \\ \text{for } n = 1, 2, \ldots, N. \end{cases} \tag{5}$$

3.4 Marginal State Probabilities

Aggregating ME solution $\{P(\mathbf{n}), \mathbf{n} \in \mathbf{Q}\}$ and after some manipulation, the following expressions for the marginal probabilities can be obtained [9]:

$$P_i(0) = \frac{1}{Z} \Big(1 + \prod_{j=1 \wedge j \neq i}^{R} \sum_{n_j=1}^{N} \left\{ \prod_{k=1}^{c} g_{jk}^{h_{jk}(\mathbf{n})} y_{jk}^{h_{jk}(\mathbf{n})} \right\} x_i^{n_j} \Big) \tag{6}$$

$$\begin{aligned} P_i(n_i) &= \frac{1}{Z} x_i^{n_i} \Big(\prod_{j=1 \wedge j \neq i}^{R} \sum_{n_j=0}^{N-n_j} x_j^{n_j} \\ &\quad \Big(\prod_{r=1}^{R} \left\{ \prod_{k=1}^{c} g_{rk}^{h_{rk}(\mathbf{n})} y_{rk}^{h_{rk}(\mathbf{n})} \right\} \Big) \Big), \\ &\quad \text{for } n_i = 1, 2, \ldots, N-1, \end{aligned} \tag{7}$$

$$P_i(N) = \frac{1}{Z} \left\{ \prod_{k=1}^{c} g_{ik}^{h_{ik}(\mathbf{n})} \right\} x_i^N y_i. \tag{8}$$

3.5 The Blocking Probability

Focusing on a tagged job within an arriving bulk at a GE/GE/c/N/PR/CBS queue, a universal closed form expression for blocking probabilities $\{\pi_i, i = 1, 2, \ldots, R\}$ can be approximately established, based on GE-type probabilistic arguments and is given by (c.f., [9])

$$\pi_i = \sum_{j=1}^{R} \sum_{k=0}^{N} \delta_i^L (1 - \sigma_i)^{N-k} P(\mathbf{n}_j), \tag{9}$$

where

$$L = \begin{cases} c & \text{if } k = 0, \\ max(0, c - k) & \text{if } j \le i \ \& \ k > 0, \\ min(c, k) & \text{if } j > i \ \& \ k > 0; \end{cases}$$

$\sigma_i = (C^2_{a\,i} + 1)/2$ and $r_i = (C^2_{s\,i} + 1)/2$, are the inter-arrival time and service time stage selection probabilities respectively and $\delta_i = r_i/(r_i(1 - \sigma_i) + \sigma_i)$.

3.6 The Lagrangian Coefficients

It is assumed, as in earlier works (c.f., [5,10]), that the Lagrangian coefficients $\{g_i, x_i, i = 1, \ldots, R\}$ of the ME solution (2) for GE-type queues and networks are largely invariant to the buffer size N. These coefficients can be, therefore, approximated via closed form asymptotic queueing theoretic expressions based on the ME solution of the corresponding infinite capacity GE/GE/c/PR queue at equilibrium (c.f., [8]). To this end, appropriate formulae for the calculation of $\{g_i, x_i, i = 1, \ldots, R\}$ can be established [9]. Finally, using the flow balance condition (1) and the closed-form expressions for the normalising constant, Z, the aggregate probabilities $\{P(n), n = 0, 1, \ldots, N_1\}$ and the blocking probabilities $\{\pi_i, i = 1, \ldots, R\}$, the Lagrangian coefficients $\{y_i, i = 1, 2, \ldots, R\}$ can be determined, after some manipulation, as follows:

$$\begin{aligned} y_i \quad = \quad & \frac{\rho_i}{\displaystyle\sum_{\mathbf{S} \in A_i^N} x_i^N \left\{ \prod_{k=1}^{c} g_{ik}^{h_{ik}(\mathbf{S})} \right\} \prod_{j=i+1}^{R} x_j^{n_j}} \\ & \left(1 + \sum_{v=1}^{N-1} \left(\sum_{\mathbf{S} \in A_i^N} \prod_{i=1}^{R} \left\{ \prod_{k=1}^{c} g_{ik}^{h_{ik}(\mathbf{S})} \right\} x_i^{n_i} \right) \right. \\ & - \frac{1}{\rho_i} \sum_{\mathbf{S} \in A_i^N} x_i^N \left\{ \prod_{k=1}^{c} g_{ik}^{h_{ik}(\mathbf{S})} \right\} \prod_{j=i+1}^{R} x_j^{n_j} \\ & - \sum_{k=0}^{c-1} \delta_i^{(c-k)} (1 - \sigma_i)^{N-k} \\ & + \sum_{j=1}^{i} \sum_{k=c}^{N-1} (1 - \sigma_i)^{N-k} P^j(k) \\ & \left. + \sum_{j=i+1}^{R} \sum_{k=c}^{N-1} (1 - \sigma_i)^{N-k} P^j(k) \right), \qquad (10) \end{aligned}$$

for $i = 1, 2, \ldots, R$.

Note that by defining appropriate z-transforms (e.g., Williams and Bhandiwad [11]), formulae (2)-(10) can be transformed, as appropriate, into cost-effective computationally recursive expressions (c.f., [9]).

4 Numerical Results

This section presents an example in order to illustrate the usability and credibility of the proposed methodology as simple and cost-effective solution. The considered example is based on a GSM/GPRS system that provides voice and data services. The voice calls are assumed to have average call duration of 100s while the data calls are modelled in this example at burst level assuming that a number of packets will be buffered before transmission and, therefore, they can be transmitted as one session. The average burst size is assumed to be 12.5 Kbyte which will be investigated with a range of SCV values. As stated before, the model assumes preemptive priority for voice calls over data sessions. The system also assumes that blocked calls of both types are not lost immediately but are queued for further service. This assumption will affect mainly the data connections as the voice call will be able to push out ongoing data connection.

The numerical results obtained for the above model cover the marginal utilization of each type of service versus aggregate arrival rate validated against simulation (Figures 4 and 5) . The aggregate arrival rate is composed of 80% of voice traffic and 20% of data traffic. The simulation is performed using QNAP2 package (QNAP-2 [12]) with 95% confidence intervals. The curves show very good matching between the analytical solution and simulation. It can also be seen that the data traffic will cause relatively very small extra utilization on the network because of the data can use the full available data rate left by the voice.

Finally, Figures 6 and 7 give an indication on the powerfulness of the approach to study more results varying different parameters. In this case, the mean queue length of both service classes is shown using different SCV values for the burst size of the data sessions versus the buffer size.

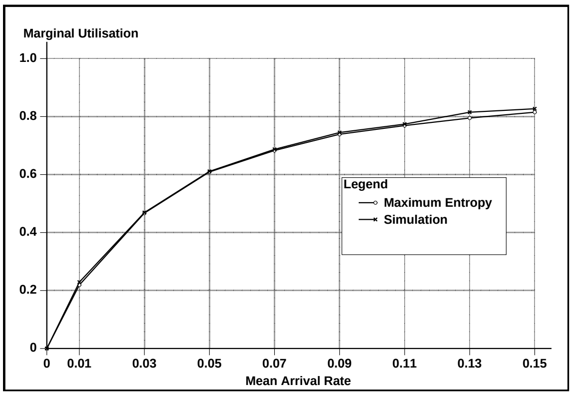

Figure 4: Marginal Utilisations for Class 1 Calls

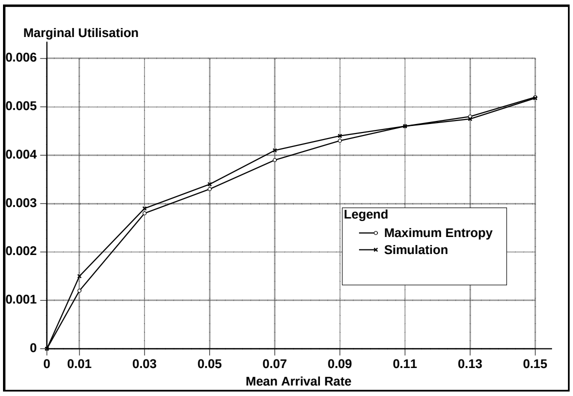

Figure 5: Marginal Utilisations for Class 2 Calls

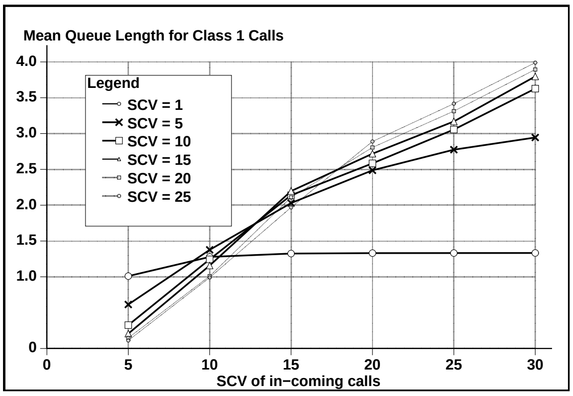

Figure 6: Effect of varying degrees of SCV on MQLs of Class 1 at different buffer sizes

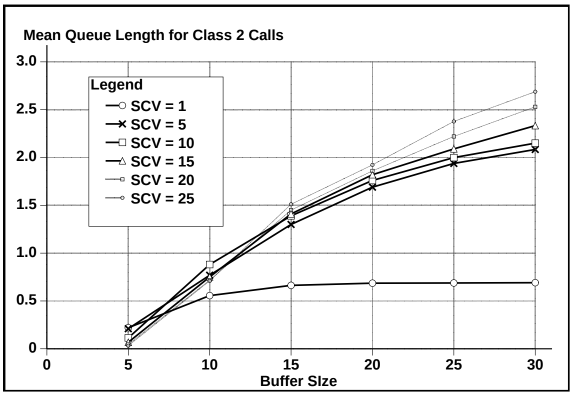

Figure 7: Effect of varying degrees of SCV on MQLs of Class 2 at different buffer sizes

5 Conclusions and Future Work

An analytic framework is devised for the performance modelling and evaluation of a GSM/GPRS wireless cell supporting multiple classes of both voice calls and data packets of traffic under ASS handling scheme. The GSM/GPRS cell is modelled by a GE/GE/c/N/PR/CBS queue having Compound Poisson arrival processes (CPPs) with geometrically distributed batches (or, equivalently, Generalised Exponential (GE)-type interarrival times) and GE-type service times under PR priority rule and CBS management scheme. The traffic of data packets and voice calls is assumed to be bursty with different arrival rates, interarrival and service times SCVs, file burst sizes. The GE/GE/c/N/PR/CBS queue is analysed via the principle of ME and new closed form expressions for state and blocking probabilities are obtained. Typical numerical examples are included to confirm the relative accuracy of the ME solution against simulation at 95% confidence intervals and also to assess the effect of external GE-type bursty traffic upon the performance of the cell.
The analytic methodology provides simple and robust quantitative tools for the performance modelling, evaluation and prediction of GSM/GPRS wireless cells. The methodology can be extended to analyse QNMs of networks of wireless cells using the principle of ME and the concept of QNM system decomposition (c.f.,[5,9,10]).

Acknowledgement

We wish to thank our industrial partners of the EU IST Project IASON for their valuable advice towards the specification of our GSM/GPRS queueing models.

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Biographies

Irfan Awan received his PhD from the Department of Computing, Bradford University, UK (1997). During his PhD studies, he developed cost effective approximate analytical tools for the performance evaluation of complex queueing networks. His research mainly focused on service and space priorities in order to provide quality of service and to control the congestion in high speed networks. After completing his PhD he joined GIK Institute of Engineering Sciences and Technology, Pakistan as an assistant professor and has been teaching various subjects related to network communications for two years. In 1998 and 1999, he spent summer terms with the Performance Modelling Group, University of Bradford. In 1999 he joined the Department of Computing, University of Bradford as a Lecturer and is a module coordinator for "Concurrent and Distributed Systems" and "Intelligent Network Agents". His recent research lies in developing analytical tools for the performance of mobile and high speed networks.

Demetres Kouvatsos received a BSc degree in Mathematics, Athens National University (1970), a MSc degree in Statistics, Victoria University of Manchester (1971) and a PhD degree in Computation, UMIST, University of Manchester (1974). He has a chair in Computer and Communication Systems Modelling and is the Head of the School of Computing and Mathematics, University of Bradford.

Professor Kouvatsos has pioneered new and cost-effective methodologies for the approximate analysis of arbitrary queueing network models (QNMs) for the performance evaluation and engineering of computer and telecommunication systems. He has directed several EPSRC (UK) and industrial research projects and is the author or co-author of many papers as well as the editor of research books and special journal issues in the performance modelling field. His latest technical interests include traffic modelling and characterisation, analytic methodologies for discrete time QNMs and performance modelling and evaluation of high speed switch architectures and the Internet.

He acted as the Chairman of seven International Federation of Information Processing (IFIP) Working Conferences on the Performance Modelling and Evaluation of ATM & IP Networks (1993-98, 2000) and as the Co-Chairman of the 3rd and 4th International Workshops in"Queueing Networks with Finite Capacity" (1995, 2000). He also served as the Technical Track Chairman of the "Analytical and Numerical Modelling Techniques" Conference of ESM '98 and as a member of many Programme Committees of international events in the field. His professional association include memberships with the IFIP Working Group WG 6.3 on the Performance of Computer Networks and the UK Performance Engineering Specialist Group of BCS and a Fellowship with the Royal Statistical Society, UK. He is also an elected member of the EPSRC College and the recipient of the IFIP Silver Core Award in recognition of his academic services to IFIP.

Khalid Al-Begain received his High Diploma (1986), the Specialization Diploma of Communication Engineering (1988) and his Ph.D. degree in Communication Engineering (1989) from the Technical University of Budapest in Hungary. From 1990 to 1996 he held the position of a Assistant Professor at the Deptartment of Computer Science of the Mu'tah University in Jordan. Then he became a Associate Professor at the same university. In 1997 he moved to the Department of Computer Science at the University of Erlangen-Nuremberg in Germany as Alexander von Humboldt research fellow. Then, he spent one year as Guest Professor at the Chair of Telecommunications, Dresden University of Technology, Germany. Since Sept. 2000, he has been Senior Lecturer and Director of Postgraduate Research in the Department of Computing of the University of Bradford, UK. He co-authored the book "Practical Performance Modelling" published by Kluwer AP and more than 60 journal and conferences papers. He is senior member of the IEEE and many other scientefic organisations. He also serves as Conference Chair for the 10th International Conference on Analytical and Stochastic Modelling Techniques and Applications (ASMTA'03) to be held in Nottingham,UK in June 2003. His research interests are performance modelling and analysis of computer and communication systems and analytical modelling and design of wireless mobile networks. He is also interested in Mobile Computing research.