EUROPEAN TRANSACTIONS ON TELECOMMUNICATIONS
Euro. Trans. Telecomms. 2005; **16**:309–316
Published online 29 September 2004 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/ett.1000

Mobile Networks

Modeling the access to a wireless network at hot spots

L. Breuer[1], V. Klimenok[2], A. Birukov[2], A. Dudin[2] and Udo R. Krieger[3]*

[1]*Informatik, Universität Trier, D-54286 Trier, Germany*
[2]*Belarus State University, 4 F. Skorina Ave, 220050 Minsk, Belarus*
[3]*Otto-Friedrich University, D-96045 Bamberg, Germany*

SUMMARY

In teletraffic engineering, the effective design of wireless networks providing voice and data services at hot spots is of great practical importance. This paper presents a model of such networks in terms of a BMAP/PH/N retrial queue. Due to the batch occurrence and high correlation of the traffic, it is decisive to choose the correct Batch Markovian Arrival (BMAP) representation of the empirically observed streams of call requests. The numerical results show that there are great differences in important performance measures due to different structures of the chosen BMAP which have the same fundamental rate and the same coefficient of variation of the inter-arrival times. The paper again provides evidence that 'correlation matters'. Yet, further examples show that the coefficient of correlation is not the single characteristic (besides the fundamental rate and coefficient of variation) of the arrival process that has an influence on the performance of the network. Copyright © 2004 AEI.

1. INTRODUCTION

Currently, the design of fast growing radio access networks of the second generation like GSM and its enhanced variant with the data bearer service GPRS provides a major challenge to teletraffic engineering. Particularly, the network design of hot spots with very high sporadic demand caused by surges of suddenly arriving mobile subscribers requires adequate engineering tools. Such situations typically arise at access points related to mass transportation like airport, train or bus terminals, hotels or exhibition areas where large groups of subscribers arrive simultaneously and intend to satisfy their communication needs immediately with satisfactory quality of service (QoS).

Considering radio access networks from an engineering perspective, a variety of parameters have a substantial influence on the perceived quality of the data transmission in the underlying wireless circuit-switched communication systems due to the complex structure of the involved protocol stack (see Figure 1).

In particular, the fast dynamics of the customer behavior including their arrival and communication patterns should be modeled carefully. Considering the management of transmission resources over a GSM link, the calls of new customers initiate new transport connections that seize voice slots in the consecutive TDMA frames of a frequency band allocated to an access point at the air interface, i.e. a base station of a GSM network (see Figure 1). The latter are allocated during the holding time of a connection in a cell, i.e. the cell residence time, to transfer the corresponding radio blocks that carry the voice samples of a communication between the terminals of sender and receiver.

Since the number of voice slots is limited to seven among the eight slots provided by a single TDMA frame in one radio frequency channel (RFCH), the latter create a critical resource. They constitute a transport system of logical channels at the data link layer supporting the connections initiated at the transport layer (see Figure 1). Even if several RFCHs are available in a radio cell operated by a

* Correspondence to: Udo R. Krieger, Otto-Friedrich University, D-96045 Bamberg, Germany. E-mail: udo.krieger@ieee.org

Received 10 July 2003
Revised 2 November 2003
Accepted 1 April 2004

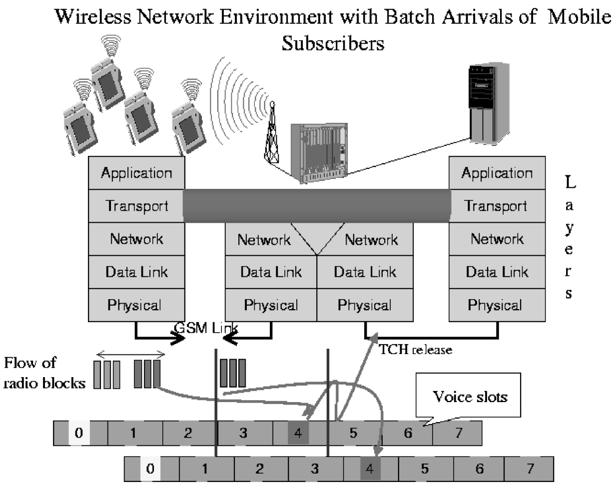

Figure 1. Resource management at hot spots in a wireless network.

base station, it may happen that the new call of a customer has to be blocked due to a lack of radio resources. In this case, the customer will try to get access to the network by redialing. Thus, from the perspective of teletraffic engineering, it is very important to understand the resource allocation and seizure processes subject to the batch arrival and general holding time characteristics as well as the redialing behavior of customers in the sketched hot spots.

In this paper, the outlined access to a wireless network at such a hot spot is modeled at the connection level by a BMAP|PH|N retrial system with a Batch Markovian Arrival (BMAP) process, phase-type (PH) distributed holding times of connections at the transport layer and exponential retrials of those calls which cannot seize a logical transport channel at the GSM link layer upon arrival. For this model, an analysis has been provided by Breuer, Dudin and Klimenok [2]. Here, it is applied in several experiments to compute numerical results where the main independent variable is determined by the structure of the arrival process. Regarding the network design, the required number of servers to provide a certain guaranteed QoS is studied.

The developed model provides a further step towards a better analysis of resource reservation in mobile environments of second and third generation. It may guide the advanced resource management of new adaptive multimedia applications that have specified their required QoS configurations in advance (cf. [5]).

The paper is organized as follows. First, the loss model BMAP/PH/N with retrials is described. In Section 3, its relevant performance measures are evaluated illustrating the influence of the correlation structure of the arrival process. Finally, some conclusions are presented.

2. THE MODEL

The performance evaluation of the access to a wireless network at hot spots, for example at a terminal of a mass transportation system, constitutes the object of our investigation. In such an environment, a base station with a certain bandwidth is located close to a number of gates in order to serve arriving or departing customers. The bandwidth is assumed to allow the simultaneous processing of N calls. Thus, we have a loss system with N servers describing the parallel logical transport channels.

The duration of the calls in a single cell shall be identically distributed and independent among customers. This duration is modeled by the versatile PH distribution introduced by Neuts [7]. The service of a customer by a server is governed by the directing process m_t. The state space of this continuous-time Markov chain m_t is determined by $\{1, \ldots, M\}$. The initial state of the process m_t at the service invocation epoch is determined by the probabilistic row-vector $\beta = (\beta_1, \ldots, \beta_M)$. The transitions of the process m_t which do not lead to service completion are defined by the non-diagonal entries of an irreducible matrix S of size $M \times M$. The intensities of transitions which lead to service completion are defined by the vector $S_0 = -S\mathbf{1}$. Here and in the sequel $\mathbf{1}$ denotes the column vector consisting of all ones. If the dimension of the vector is not clear by the context, it is indicated as a subscript. The service time distribution function has the form $B(x) = 1 - \beta e^{Sx}\mathbf{1}$. A more detailed description of the PH-type service time distribution can be found, for example in Neuts [8].

Since customers come in large groups when a transport entity, for example a plane, arrives at a gate or shortly before boarding time, it is natural to assume that a highly correlated stream of calls applies to the network. Furthermore, calls of many customers at roughly the same time are very likely, which leads to the possibility of batch arrivals. Such arrival streams are best modeled by BMAPs (see Lucantoni [6]). We denote the directing process of the BMAP by $\nu_t, t \geqslant 0$. The state space of this irreducible continuous-time Markov chain ν_t is given by $\{0, 1, \ldots, W\}$. The behavior of the BMAP is characterized completely by the matrix generating function $D(z) = \sum_{k=0}^{\infty} D_k z^k$, $|z| < 1$. The matrix D_k characterizes the intensities of the transitions of the process ν_t which are accompanied by generating a batch of k calls, $k \geqslant 0$. The matrix $D(1)$

represents the generator of the process $\nu_t, t \geqslant 0$. The invariant probability vector $\vec{\theta}$ of this process is calculated as a solution of the following system of the linear algebraic equations: $\vec{\theta}D(1) = \vec{0}, \vec{\theta}\mathbf{1} = 1$. The average intensity λ, i.e. the fundamental rate, of the BMAP is defined by $\lambda = \vec{\theta}D'(z)|_{z=1}\mathbf{1}$, and the intensity λ_g of group arrivals by $\lambda_g = \vec{\theta}(-D_0)\mathbf{1}$. The variance v of intervals between group arrivals is calculated by

$$v = 2{\lambda_g}^{-1}\vec{\theta}(-D_0)^{-1}\mathbf{1} - {\lambda_g}^{-2}$$

while the coefficient of correlation c_{cor} of the intervals between successive group arrivals is given by

$$c_{\text{cor}} = \frac{({\lambda_g}^{-1}\vec{\theta}(-D_0)(D(1) - D_0)(-D_0)^{-1}\mathbf{1} - {\lambda_g}^{-2})}{v}$$

If customers find the system busy, they will try to call again a short time later. They are assumed to react independently of each other and every one in exponentially distributed intervals (i.e. according to a Poisson process) with the same rate α. If the offered batch of these primary calls finds several servers idle upon arrival, the primary calls occupy the corresponding number of servers. If the number of idle servers is not sufficient (or all servers are busy), the rest of the batch (or the complete batch) enters a virtual waiting room called orbit. These calls are said to be repeated calls.

Thus, we derive a BMAP/PH/N retrial model, if we take all these sketched properties into account. Queues of this type have been examined extensively by Breuer, Dudin and Klimenok [2]. Our paper contains a more detailed application of the related theoretical results to wireless networks at hot spots.

To find the stationary characteristics of the BMAP/PH/N retrial model, the multi-dimensional process

$$\xi_t = \{i_t,\, n_t,\, \nu_t,\, m_t^{(1)}, \ldots, m_t^{(n_t)}\},\ t \geqslant 0$$

is considered in Reference [2] where

- i_t is the number of calls in the orbit, $i_t \geqslant 0$,
- n_t is the number of busy servers, $n_t = \overline{0, N}$,
- $m_t^{(j)}$ is the state of the directing process of the service on the jth busy server, $m_t^{(j)} = \overline{1, M}$, $j = \overline{1, n_t}$

  (we assume here that the busy servers are enumerated in the order of their seizure, i.e. the server, which begins the service, is assigned the maximal number among all busy servers; when some server finishes the service, the servers are correspondingly enumerated again),
- ν_t is the state of the directing process of BMAP, $\nu_t = \overline{0, W}$, at the epoch $t, t \geqslant 0$.

It is easy to see that this process is an irreducible Markov chain. We denote the stationary probabilities of this process by

$$\begin{aligned} &p(i, n, \nu, m^{(1)}, \ldots, m^{(n)}) \\ &\quad = \lim_{t\to\infty} P\{\, i_t = i,\ n_t = n,\ \nu_t = \nu,\ m_t^{(1)} = m^{(1)}, \\ &\quad = \ldots m_t^{(n)} = m^{(n)}\} \end{aligned} \tag{1}$$

for $i \geqslant 0$, $\nu = \overline{0, W}$, $m^{(j)} = \overline{1, M}$, $j = \overline{1, n}$ and $n = \overline{0, N}$.

Enumerating the states of the Markov chain $\xi_t, t \geqslant 0$, in lexicographical order, we form the row-vector $\vec{p}_i$ of the corresponding stationary-state probabilities $p(i, n, \nu, m^{(1)}, \ldots, m^{(n)}), i \geqslant 0$. Note that the dimension of these vectors is equal to $K = (W+1)(M^{N+1} - 1)/(M-1)$. In Reference [2] the problem of finding conditions for the existence of the limits Equation (1) is solved as follows.

Proposition. *A sufficient condition for the existence of the stationary distribution is given by*

$$\rho = \frac{\lambda}{\bar{\mu}} < 1 \tag{2}$$

where λ is the average arrival rate,

$$\bar{\mu} = \vec{y} S_0^{\oplus N}\, \mathbf{1}_{M^{N-1}} \tag{3}$$

and $\vec{y}$ is the unique solution of the following system of linear algebraic equations:

$$\begin{aligned} \vec{y}(S^{\oplus N} + S_0^{\oplus N}(I_{M^{N-1}} \otimes \beta)) &= 0 \\ \vec{y}\mathbf{1} &= 1 \end{aligned} \tag{4}$$

Here $S^{\oplus N} def = \underbrace{S \oplus \ldots \oplus S}_{N}$, $S_0^{\oplus N} = \sum_{m=0}^{N-1} I_{M^m} \otimes S_0 \otimes I_{M^{N-m-1}}$, *and I_l denotes the identity matrix of dimension $l, l \geqslant 1$. The symbol $\otimes$ denotes the Kronecker product of matrices.*

In Reference [2], a stable numerical algorithm to calculate the probability vectors $\vec{p}_i, i \geqslant 0$ has been elaborated. However, the corresponding paper does not contain any information about numerical experiments. Moreover, the non-trivial problem to calculate some important performance measures of the model based on the knowledge of the probability vectors $\vec{p}_i, i \geqslant 0$ has not been discussed in that paper.

The most interesting performance measures are the following:

- the mean number L_0 of requests in the orbit, i.e. the mean number of customers that do not succeed to set up a connection in the network;

- the probability P_0 of an empty orbit, i.e. the probability that all customers are served by the network;
- the probability P_{im} that an arbitrary call request will be served by the network immediately, i.e. that a customer can use the network upon the first trial to call.

The latter can be seen as an equivalent to Erlang's loss formula, since it describes the performance of the system from the individual perspective of an arriving fresh customer and, thus, yields the immediatest indicator of customer satisfaction. The first two performance measures are important from the system operator's point of view.

The mean number of requests in the orbit is computed by $L_0 = \sum_{i=1}^{\infty} i\vec{p}_i\mathbf{1}$. The probability P_0 of an empty orbit is just $\vec{p}_0\mathbf{1}$. A formula for the probability P_{im} that an arbitrary customer succeeds to reach the transport service without retrial is given by:

$$P_{im} = \frac{1}{\lambda}\sum_{m=1}^{N}[\vec{P}(1)]_{N-m}\sum_{k=0}^{m}(k-m)(D_k \otimes I_{M^{N-m}})\mathbf{1} \qquad (5)$$

Here $[\vec{P}(1)]_m$ represents a vector consisting of those entries of the vector $\vec{P}(1) = \sum_{i=0}^{\infty}\vec{p}_i$ that correspond to the state m of the process $n_t, t \geqslant 0$.

Since the batch arrivals are the essential feature of the considered model, it is useful to have a formula for the calculation of $P_{im}^{(k)}$. The latter denotes the probability that an arbitrary customer succeeds to reach the service without retrial subject to his arrival in a group of k customers. It is determined by

$$P_{im}^{(k)} = \sum_{m=0}^{N-k} P_m^{(k)} + \sum_{m=\max\{0,N-k+1\}}^{N-1} \frac{N-m}{k} P_m^{(k)}, \quad k \geqslant 1 \quad (6)$$

Here $P_m^{(k)}$ is the probability that m servers are busy at the epoch of a batch arrival of k customers, $m = \overline{0,N}, k \geqslant 1$. It is calculated as follows:

$$P_m^{(k)} = \frac{[\vec{P}(1)]_m(D_k \otimes I_{M^m})\mathbf{1}}{\vec{\theta}D_k\mathbf{1}}, \quad m = \overline{0,N}, \quad k \geqslant 1$$

The numerical results at the end of the present paper will show that the correlation structure of the arrival stream has a strong influence on the performance metrics of the sketched system. This feature illustrates that more classical approaches, which model the arrival streams by Poissonian group arrival processes, yield results which are too optimistic and thus unrealistic.

Besides the variation of the structure of the arrival process, we will examine the loss system for $N \in \{7, 14, 22\}$ channels that are available to serve the customers' calls. Due to the technical design of the GSM air-interface these numbers typically appear in wireless networks.

3. NUMERICAL RESULTS

Using the infrastructure of the software package 'SIRIUS++' (see References [3, 4]), the algorithms elaborated in Reference [2] have been realized and have now been integrated into this package. 'SIRIUS++' has been developed at the Belarusian State University to calculate the performance measures for a variety of queueing models with BMAP input.

The model described in the previous section has been evaluated for the possible numbers $N \in \{7, 14, 22\}$ of servers and several types of arrival processes. To reduce the computational costs, the service time distribution has been chosen as an exponential one with rate $\mu = 10$ and it is constant in most examples. Further, in all examples the retrial rate $\alpha = 20$ has been chosen.

Thus, the results are mainly dependent on the arrival process. This setting leads to the purpose of the paper, namely, to show that the main performance measure P_{im}, i.e. the probability that an arbitrary customer will be served by the network without the need of redialing, strongly depends on the structure of the arrival process. One of the most important parameters of this scenario is given by the coefficient of correlation. However, this is not the only variable determining the performance of the system.

In the following tables, we depict numerical results for several arrival processes. Regarding the performance measures, we state the mean number L_0 of requests in the orbit, the probability P_0 of an empty orbit, as well as the probability P_{im}. Besides the structure of the arrival process these attributes also depend on the number N of available servers.

In the first experiment, all arrival processes employed in the numerical evaluation have an arrival intensity $\lambda = 27.5$ and the coefficient of variation is equal to 12.2733 to guarantee comparable quantities. Thus, the differences in performance can be attributed to the different correlation of the inter-arrival time intervals of the arrival processes. First, we show results for four different BMAPs with correlation coefficients $c_{\text{cor}} \in \{0.1, 0.2, 0.3, 0.4\}$. The first BMAP with correlation $c_{\text{cor}} = 0.1$ is given by the characteristic matrices

$$D_0 = \begin{pmatrix} -5.874 & 0.000 \\ 0.000 & -0.129 \end{pmatrix} \quad \text{and} \quad D_i = \begin{pmatrix} 0.586 & 0.002 \\ 0.010 & 0.003 \end{pmatrix}$$

for $i = 1, \dots, 10$. Here, we obtain the results:

N	L_0	P_0	P_{im}
7	1.7	0.67	0.53
14	0.1	0.95	0.94
22	0.0	1.00	1.00

This outcome clearly shows that for such an arrival process $N = 7$ servers are not sufficient, while the performance with $N = 14$ servers will usually satisfy the customer demands. The second BMAP with correlation $c_{\mathrm{cor}} = 0.2$ is given by

$$D_0 = \begin{pmatrix} -6.745 & 0.000 \\ 0.000 & -0.219 \end{pmatrix} \quad \text{and} \quad D_i = \begin{pmatrix} 0.670 & 0.004 \\ 0.012 & 0.010 \end{pmatrix}$$

for $i = 1, \dots, 10$. Then, we obtain:

N	L_0	P_0	P_{im}
7	2.1	0.66	0.48
14	0.2	0.95	0.92
22	0.0	1.00	0.99

To achieve an appropriate QoS, it seems again advisable to use $N = 14$ servers. However, one can already see a slight deterioration of the performance due to the higher correlation. This will continue for higher correlations, as we will see for the BMAP with correlation $c_{\mathrm{cor}} = 0.3$ and the characterization

$$D_0 = \begin{pmatrix} -8.771 & 0.000 \\ 0.000 & -0.354 \end{pmatrix} \quad \text{and} \quad D_i = \begin{pmatrix} 0.867 & 0.010 \\ 0.012 & 0.024 \end{pmatrix}$$

for $i = 1, \dots, 10$. We get:

N	L_0	P_0	P_{im}
7	3.7	0.63	0.35
14	0.3	0.92	0.87
22	0.0	0.99	0.99

Now a number $N = 14$ of servers will not be sufficient anymore if the QoS includes the guarantee that 90% of the customers should be able to call without retrial. This trend is supported by the arrival process with the highest correlation $c_{\mathrm{cor}} = 0.4$ of the BMAP defined by

$$D_0 = \begin{pmatrix} -17.231 & 0.000 \\ 0.002 & -0.559 \end{pmatrix} \quad \text{and} \quad D_i = \begin{pmatrix} 1.705 & 0.018 \\ 0.006 & 0.049 \end{pmatrix}$$

for $i = 1, \dots, 10$. We obtain the results:

N	L_0	P_0	P_{im}
7	47.9	0.64	0.09
14	1.3	0.85	0.59
22	0.2	0.96	0.92

Here, even $N = 22$ will be barely enough to achieve the QoS defined previously. Comparing these four arrival processes, we see that only an increase of the coefficient of correlation from 0.2 to 0.4 effects that we need eight additional servers to achieve a performance level of $P_{im} = 0.92$.

The stated examples suggest a simple dependence of the performance on the coefficient of correlation. In the following experiment, the next two examples show that this would be too crude as a rule of thumb for the design of an access network. First, we examine a system with an batch interrupted Poisson process (BIPP) having a BMAP representation

$$D_0 = \begin{pmatrix} -1.0 & 1.0 \\ 0 & -10.0 \end{pmatrix} \quad \text{and} \quad D_i = \begin{pmatrix} 0.0 & 0.0 \\ 0.1 & 0.9 \end{pmatrix}$$

for $i = 1, \dots, 10$. This arrival process has the same intensity $\lambda = 27.5$, but a coefficient of correlation $c_{\mathrm{cor}} = 0.0$. Thus, we would expect a better system performance. But the results

N	L_0	P_0	P_{im}
7	3.1	0.64	0.39
14	0.3	0.92	0.87
22	0.02	0.99	0.99

show a performance metric comparable to the sketched BMAP example with $c_{\mathrm{cor}} = 0.3$. It can be intuitively explained by the following bad bursty-traffic feature of the BIPP: intervals with high arrival rate alternate with rather long intervals without any arrival.

Another example with the coefficient of correlation $c_{\mathrm{cor}} = 0.0$ is given by the following interrupted Erlang renewal process (of order 2) with batch arrivals. It is characterized by

$$D_0 = \begin{pmatrix} -1.5 & 1.5 & 0.0 \\ 0.0 & -15.0 & 15.0 \\ 0.0 & 0.0 & -15.0 \end{pmatrix}$$

and

$$D_i = \begin{pmatrix} 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.15 & 1.35 & 0.0 \end{pmatrix}$$

for $i = 1, \dots, 10$. Again this arrival process has an intensity $\lambda = 27.5$ and a coefficient of correlation $c_{\mathrm{cor}} = 0.0$. The results read:

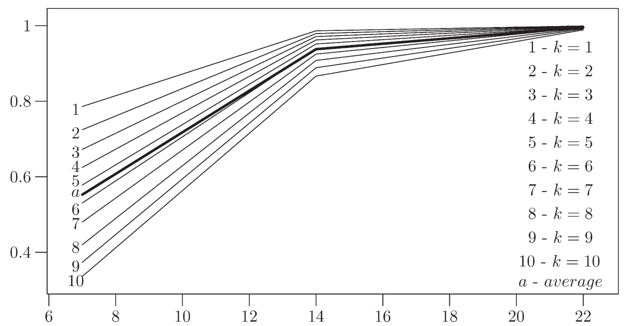

Figure 2. Dependence of the probability $P_{im}^{(k)}$ that a call request arriving in a group of size k is immediately served on the number N of channels.

N	L_0	P_0	P_{im}
7	1.4	0.68	0.57
14	0.1	0.97	0.97
22	0.0	1.00	1.00

Although the coefficient of correlation is the same as that one arising from the BIPP, the performance of the system is much better. The QoS is comparable to the BMAP example with $c_{\text{cor}} = 0.1$. This property clearly indicates that the coefficient of correlation is not the single determining variable.

It is the aim of the next experiment to demonstrate the dependence of the immediate access probability of an arbitrary customer on the batch size $k = \overline{1, 10}$ of his group. Such a dependence is illustrated by Figure 2. Here those data are used that correspond to the first BMAP considered in this section. The bold line represents the immediate access probability P_{im} of an arbitrary customer.

In the previous experiments, the service time distribution is assumed to be exponential. The investigation of the impact of a PH service time distribution, for example the impact of the coefficient of variation, seems to be an interesting problem as well. However, such an experiment, which requires the calculation of the performance measures for different classes of PH distributions like Erlangian, Coxian, or hyper-exponential ones and different numbers N of servers, deserves separate considerations. The reason is the following. Some computer problems arise when we deal with a relatively big N and PH distribution. If, for instance, both controlling processes of the BMAP input and PH service have only two states and $N = 6$, then 254 is the dimension of the underlying matrices processed in the calculations. Since a lot of such matrices should be kept in the computer memory (see algorithm in Reference [2]), the program execution on a PC is rather memory consuming. Thus, additional technical efforts are required to perform the detailed experiments. Therefore, we can present here just a limited illustration of those calculations for a non-exponential service time distribution.

Table 1. Dependence of the performance characteristics on the number of servers in case of an exponential service time distribution.

N	2	3	4	5	6
P_{im}	0.00705	0.14748	0.30079	0.43845	0.55961
L_0	212.39597	8.61619	3.43471	1.90348	1.18495
P_0	0.08506	0.34413	0.51024	0.62207	0.70488

Table 2. Dependence of the performance characteristics on the number of servers in case of an Erlangian service time distribution.

N	2	3	4	5	6
P_{im}	0.00682	0.14722	0.29974	0.43639	0.55622
L_0	211.64788	8.36364	3.45509	1.95911	1.24322
P_0	0.08472	0.34108	0.50349	0.61333	0.69549

We assume that the first BMAP described in this section is selected. In Table 1, we present the main performance characteristics of the system in the case of an exponential service with the mean value 0.05. Table 2 contains the same characteristics for an Erlangian service time distribution of order two with the same mean. Results for $N = 1$ are not presented because the stationary state distribution of the system does not exist in this case.

The comparison of Tables 1 and 2 shows that the values of the characteristics do not differ very essentially. Hence, the numerical results sketched for the systems with larger values of N and exponential service time can hopefully be applied to estimate the characteristics of systems with PH type service time distribution.

4. CONCLUSIONS

The access to a wireless network at hot spots has been modeled at the connection level by a BMAP/PH/N retrial queue. Regarding this loss model numerical results have been obtained by algorithms developed in Reference [2]. In these experiments, the structure of the arrival process has been the main independent variable. The target variable is determined by the number of servers that is necessary to provide a certain guaranteed level of QoS. The latter is determined by the probability P_{im} that an arbitrary customer can set up a connection in the network immediately upon the first call attempt.

The numerical results show great differences in the performance metric of the network. The latter must be attributed to differences in the structure of the BMAP input processes, since all arrival processes have been chosen with the same arrival intensity. The examples illustrate that the coefficient of correlation c_{cor} of the intervals between successive group arrivals has a great influence on the performance measures. But it has also been shown that it is not the only determining factor.

It can be concluded as a consequence for the practical design of such wireless networks at hot spots that the models of such access structures should grasp as many features of the empirical arrival streams as possible. Model fitting by simple statistics such as the arrival intensity and the coefficient of correlation alone is not sufficient for realistic modeling. Up to now, the only method of fitting BMAPs to empirical arrival streams beyond moment matching has been stated by Breuer [1]. Further research should include an investigation of the properties, which exactly characterize those features of BMAPs that have an influence on the performance of the derived queueing systems, i.e. an assessment by a 'view through the queue'.

REFERENCES

1. Breuer L. An EM algorithm for batch Markovian arrival processes and its comparison to a simpler estimation procedure. *Annals of Operations Research* 2002; **112**:123–138.
2. Breuer L, Dudin A, Klimenok V. A retrial BMAP/PH/N system. *Queueing Systems* 2002; **40**(4):431–455.
3. Dudin AN, Klimenok VI, Klimenok IA, *et al.* Software 'SIRIUS+' for evaluation and optimization of queues with the BMAP-input. In *Advances in Matrix Analytic Methods for Stochastic Models*, Latouche G, Taylor P (eds). Notable Publications, Inc.: New Jersey, 2000; 115–133.
4. Dudin AN, Klimenok VI, Tsarenkov GV. Software 'SIRIUS++' for performance evaluation of modern communication networks. In *Modelling and Simulation 2002: 16th European Simulation Multi-Conference*, Amborski K, Meuth H (eds). SCS: Netherlands, 2002; 489–493.
5. Matthes M, Bachmann J, Drobnik O, Krieger UR. A QoS-management system for adaptive applications supporting mobility and end-to-end guarantees. In *Proceedings of the ASTED International Conference Wireless and Optical Communications* (WOC 2002), Banff, USA, July 2002.
6. Lucantoni DM. New results on the single server queue with a batch Markovian arrival process. *Communications in Statistics Stochastic Models* 1991; **7**(1):1–46.
7. Neuts MF. Probability distributions of phase type. In *Liber Amicorum Prof. Emeritus H. Florin*, Department of Mathematics, University of Louvain: Belgium, 1975; 173–206.
8. Neuts MF. *Matrix-Geometric Solutions in Stochastic Models*. The Johns Hopkins University Press: Baltimore, 1981.

AUTHORS' BIOGRAPHIES

Lothar Breuer received his Ph.D. at the University of Trier, Germany, in 2000. He works in the fields of queueing theory and stochastic processes. Currently, he is employed as an assistant professor at the University of Trier, Germany.

Valentina I. Klimenok has got the Ph.D. in Probability Theory and Mathematical Statistics in 1992 and the Doctor of Science degree in 2002 from the Belarus State University. Currently, she is the leading scientific researcher of the Laboratory of Applied Probabilistic Analysis in the Belarusian State University, associate professor of the Probability Theory and Mathematical Statistics Department. She participated in scientific projects funded by INTAS, DLR (Germany), and KOSEF (Korea). Her fields of scientific interests include stochastic processes (including multi-dimensional Markov chains and Markov renewal processes), queues (controlled queues, queues with correlated input and service and queues in random environment, in particular) and their applications.

Alexander A. Birukov has got a master degree in Applied Mathematics in 2002 from the Belarus State University. Currently, he is a Ph.D. student in the Belarusian State University. His fields of scientific interests include queues (controlled queues, queues with correlated input and service) and their applications, and queueing software development.

Alexander N. Dudin has got his master degree in Applied Mathematics in 1976 from the Belarus State University, Ph.D. in 1982 from Vilnius University (now Lithuania) and the doctor of science degree in 1992 from Tomsk University (now Russia). He had scientific visits to BEZ-Systems (USA), 1993, Free University of Amsterdam, 1995, Science University of Tokyo, 1997, Korean Advanced Institute of Science and Technology, 1998, Trier University, 2000, 2003. Currently, he is the Head of the Laboratory of Applied Probabilistic Analysis in the Belarusian State University, Professor of the Probability Theory and Mathematical Statistics Department. He was the vice-chairman of the Organizing Committee of the 1st to 16th Belarus Winter Workshops in Queueing Theory (1985–2001).

Since the 17th Workshop (2003), he is the Chairman. His fields of scientific interests include stochastic processes, queues (controlled queues and queues in random environment, in particular) and their applications in telecommunications, date bases etc.

Udo R. Krieger received his M.S. degree in Applied Mathematics and the Ph.D. in Computer Science from the Technische Hochschule Darmstadt, Germany. In 1985, he joined the Research and Technology Center of Deutsche Telekom in Darmstadt, Germany. From 1994 until 2003, he has further been affiliated with the Computer Science Department of J.W. Goethe-University in Frankfurt. Since October 2003, he is affiliated with the Department of Information Systems and Applied Computer Science at the Otto-Friedrich University in Bamberg. Udo Krieger has participated in European research projects and has served on numerous technical program committees of ITC and IEEE conferences including Infocom '98. Currently, he serves on the editorial board of the *Journal Computer Networks*. His research interests include traffic management of ATM, IP and wireless networks, teletraffic theory and numerical solution methods for Markov chains. He is a member of Gesellschaft fuer Informatik, Germany and IEEE.

