NOVEL QUEUEING MODEL FOR MULTIMEDIA OVER DOWNLINK IN 3.5G WIRELESS NETWORK

Khalid Al-Begain
Mobile Computing, Communications and Networking RG
School of Computing University of Glamorgan
Pontypridd (Cardiff) CF-37 1DL, Wales, UK
E-mail: kbegain@glam.ac.uk

Alexander N. Dudin, Vilena V. Mushko
Laboratory of Applied Probabilistic Analysis
Department of Applied Mathematics and Computer Science
Belarusian State University
F. Skorina Ave. 4, Minsk-50, 200050, Belarus
E-mail: dudin@bsu.by, vmushko@tut.by

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ABSTRACT

In this paper, the model for multimedia transmission over downlink in 3.5G wireless network in terms of a queue with two priority classes, one of which has time priority while the another has space priority, is formulated. The input is described by the Batch Marked Markov Arrival Process ($BMMAP$). Service time distributions are of PH (phase) type dependent on the class of a customer. The buffer is finite, but the customers of a class having higher priority for taking into the service from a buffer (time priority) can occupy only a part of this buffer. Queueing system's behavior is described in terms of multi-dimensional continuous time skip-free to the left Markov chain. It allows to exploit an effective algorithm for calculation of the stationary distribution of the queueing system. Loss probability for customers of both classes is calculated.

1 Introduction

While Third Generation (3G) wireless systems are being intensively deployed worldwide, new proposals for enhanced data rates and quality of service provision are being standardised. One of the most promising enhancements to the widely deployed Universal Mobile Telecommunication System (UMTS) which is based on Wideband Code Division Multiple Access (W-CDMA) is called High Speed Downlink Packet Access (HSDPA) (3GPP TS, 2001) which is also referred to as 3.5G. HSDPA aims at providing data rates around 2-10Mbps on the downlink to mobile users mainly for multimedia services such as real-time and streaming video in packet-switched common channel.

On one hand, modelling of multimedia traffic over shared channel is rather complicated. Therefore, most of the studies typically investigate the problem using packet-level simulation (Bonald and Proutiere, 2003) or as data flows which can be real-time (voice or video) or non-real-time (www browsing, e-mail, ftp, or data access). Other works considered performance study of the HSDPA system taking into account system details rather than the multimedia traffic characteristics (van der Berg et al, 2005). Attempts to capture some characteristics of the multimedia traffic analytically were made by several authors such as using self-similar traffic (Crovella and Bestavros, 1995), (Kim and Hwang, 2004), Generalised Exponential (GE) Distribution (Awan and Al-Begain, 2004), or Batch Markov Arrival Process (Chakravarthy, 2001),(Dudin and Chakravarthy, 2002), (Lucantoni, 1991). A common weakness in all previous models is that even if they capture correlation which an important feature of the multimedia traffic (GE does not even capture correlation), they consider the two flows independent of each other. However, even the single multimedia stream is composed of two types of traffic; real-time (voice and/or video) and non-real-time (data) traffic flows. These flows cannot be considered as independent flows. This implies the necessity of considering two types of correlation; intra-flow and inter-flow correlation within the same multimedia stream.

On the other hand, providing Quality of Service (QoS) for multimedia traffic requires differentiated consideration of the different flows within the single multimedia stream. The real-time traffic flow requires low delay and low jitter but can tolerate some packet loss while the data component (non-real-time) is very sensitive to packet loss but can tolerate some delay or jitter. In (Al-Begain and Awan, 2004), the

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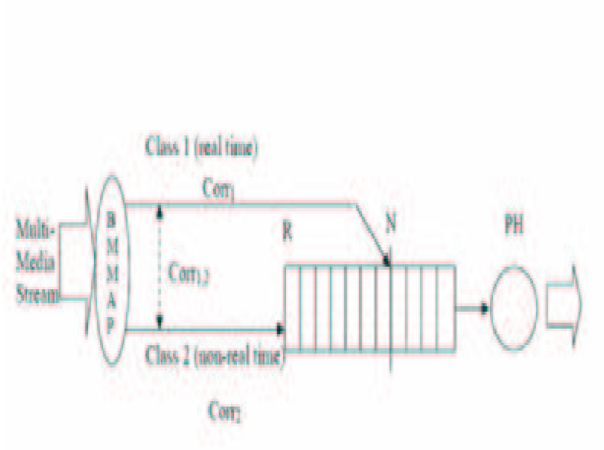

Figure 1: A simplified block diagram of the proposed buffer architecture

authors presented a multi-service class buffer model that can provide time and space prioritization based on thresholds Both priorities, however, can only be given to the same service or flow. In addition, the multimedia traffic was modelled by the GE distribution.

The paper reports on initial results of a new line of research that will bring new dimension to the analytical modelling of multimedia traffic over wireless channels. We consider a multimedia stream that is composed from two types of traffic; real-time (voice and/or video) and non-real-time (data) traffic streams (See Figure 1). Unlike most recent studies, our models present two novel features that aims at providing necessary prioritization for QoS provisioning of multimedia services. First, we consider a novel queuing model for the buffer in which the two classes of traffic that compose the one multimedia stream enjoy different priority types that suits their QoS requirement; namely time priority for real-time traffic which a threshold to control the delay and jitter while we provide space priority for the data in order to minimise packet loss. In our project, we consider a number of distributions to model both the arrival process and the service process of the multimedia traffic. In this paper, we consider a novel application of the Batch Marked Markov Arrival Process ($BMMAP$) (He, 1996) to represent the multimedia stream that consists of two classes of traffic. The main advantage of using $BMMAP$ is that it is capable of capturing both the intra-flow and inter-flow correlation.

This paper represents the first report on the results of this project, and only contains the formulation of the model and the analysis. It provides the solution and formulae for calculating packet loss probabilities for both classes. Programming of software package for numerical solution is underway. Additionally, derivation of waiting time distribution for Class 2 flow (real-time) will provide the tool to calculate the delay and jitter. This will then be the base for our optimisation goal in which we use the threshold value to obtain desirable QoS for the multimedia traffic.

2 Mathematical model

We have a single-server queue with a finite buffer of a capacity R, $R > 0$. The input flow is described by the Batch Marked Markovian Arrival Process ($BMMAP$)(see, e.g., (He, 1996)). Customers arrival in the $BMMAP$ is directed by the irreducible continuous time Markov chain $\nu_t,\ t\ \geq 0$, with a finite state space $\{0, 1, \ldots, W\}$. Sojourn time of the chain $\nu_t,\ t\ \geq 0$ in the state ν has exponential distribution with a parameter λ_ν. After this time expires, with probability $p_0(\nu, \nu')$ the chain jumps into the state ν' without generation of customers and with probability $p_k^{(l)}(\nu, \nu')$ the chain jumps into the state ν' and a batch consisting of k customers of type l (type-l customers) is generated, $k \geq 1$. Here we will assume that only two types of customers are served in the system, so $l = 1, 2$. The introduced probabilities satisfy conditions:

$$p_0(\nu, \nu) = 0,$$

$$\sum_{l=1}^{2} \sum_{k=1}^{\infty} \sum_{\nu'=0}^{W} p_k^{(l)}(\nu, \nu') + \sum_{\nu'=0}^{W} p_0(\nu, \nu') = 1,\ \nu = \overline{0, W}.$$

The parameters defining the $BMMAP$ can be kept in the square matrices D_0, $D_k^{(1)}$, $D_k^{(2)}$, $k \geq 1$ of size $\bar{W} = W + 1$ defined by their entries:

$$(D_0)_{\nu,\nu} = -\lambda_\nu,\ (D_0)_{\nu,\nu'} = \lambda_\nu p_0(\nu, \nu'),$$

$$(D_k^{(l)})_{\nu,\nu'} = \lambda_\nu p_k^{(l)}(\nu, \nu'),\ \nu, \nu' = \overline{0, W},\ k \geq 1,\ l = 1, 2.$$

Denote $D(1) = D_0 + \sum\limits_{l=1}^{2} \sum\limits_{k=1}^{\infty} D_k^{(l)}$, $\hat{D}_k^{(m)} = \sum\limits_{i=k}^{\infty} D_i^{(m)}$, $\boldsymbol{\theta}$ is the stationary probability vector of the states of the Markov chain $\nu_t,\ t\ \geq 0$.

Vector $\boldsymbol{\theta}$ is the unique solution to the system

$$\boldsymbol{\theta} = \boldsymbol{\theta} D(1), \boldsymbol{\theta}\mathbf{e} = 1.$$

Here and below $\mathbf{e}$ is the column vector of appropriate dimension consisting of all 1's.

Intensity λ_l of type-l customers arrival is calculated by

$$\lambda_l = \boldsymbol{\theta} \sum_{k=1}^{\infty} k D_k^{(l)} \mathbf{e}, l = 1, 2.$$

Type-1 customers are accepted into the system if the buffer is not full. If the size of arriving batch exceeds the available space in a buffer we assume that the corresponding part of the batch is accepted into the buffer while the rest is lost. Such a discipline is called partial admission. Disciplines of complete admission or complete rejection where the whole batch is accepted or rejected correspondingly can be handled in a similar way.

Type-2 customers have a priority with respect to type-1 customers. If at least one type-2 customers presents in the system at the service completion epoch, then type-2 customer will get the service. Type-1 customers have a chance to get service only if no one type-2 customer presents in the system. Interruption of the service is not allowed.

However, type-2 customers have more restricted access into the system. No more then N, $1 \le N < R$, type-2 customers can be accepted into the buffer. Discipline of partial admission is applied as well.

The service time of customers has PH(phase) type distribution. It means the following. Service of type-k customer is defined as a time until the continuous-time Markov chain $\eta_t^{(k)}$ having the states $(1, \ldots, M_k)$ as the transient and state 0 as absorbing one reaches the absorbing state. The initial state of the chain is selected in a random way, according to the probability distribution defined by the row-vector $(\boldsymbol{\beta}_k, 0)$, where $\boldsymbol{\beta}_k$ is the stochastic row vector of dimension M_k. Transitions of the Markov chain $\eta_t^{(k)}$, $t \ge 0$, are described by the generator $\begin{pmatrix} S^{(k)} & S_0^{(k)} \\ 0 & 0 \end{pmatrix}$ where the matrix $S^{(k)}$ is sub-generator and the column vector $S_0^{(k)}$ is defined by $S_0^{(k)} = -S^{(k)}\mathbf{e}$. The average service time is given by $\boldsymbol{\beta}_k(-S^{(k)})^{-1}\mathbf{e}$. For more details about the PH type distribution see (Neuts, 1981).

Assumption that the arriving flow is the $BMMAP$ allows to catch correlation in the input process what is very important in modelling multi-media traffic. Assumption about PH type service time distribution is some kind of trade-off between desire to consider the most general service process and possibility to have still analytically tractable Markov process as the model of the system behavior.

The proper selection of the buffer size R and the threshold N, which restricts access of the priority customers, can allow effectively control the main performance measures of the system (delay and jitter for type-2 customers and loss probability for type-1 customers). As a first step in this direction, the problem of calculation of the stationary state distribution of the Markov chain, which will be described in the next section, should be solved. Mention that this stationary distribution exists always as the state space of the Markov chain is finite, the process ν_t $t \ge 0$, is assumed to be irreducible and the so called $(\boldsymbol{\beta}_k, S_k)$ representations of PH are suggested to be irreducible.

3 Markovian process of the system states

Let $i_t^{(k)}$ be the number of type-k customers presenting in a system at the epoch t, $k = 1, 2$, ξ_t be the type of the customer is service at epoch t, ν_t be the state of the directing process of the $BMMAP$, and $\eta_t^{(\xi_t)}$ be the state of the process which defines the service at the epoch t.

In is clear that the process

$$\zeta_t = \{i_t^{(2)}, i_t^{(1)}, \xi_t, \nu_t, \eta_t^{(\xi_t)}\},\ t \ge 0,\ i_t^{(1)} = \overline{0, R - i_t^{(2)}},$$

$$i_t^{(2)} = \overline{0, N},$$

$\xi_t = k$ if type-k customer is in the service, $k = \overline{1, 2}$, $\xi_t = 0$ if the server is idle, $\nu_t = \overline{0, W}$, $\eta_t^{(k)} = \overline{1, M_k}$, is the Markov chain.

Denote the stationary state probabilities of this Markov chain by:

$$p(0,0,0,\nu) = \lim_{t \to \infty} P\{i_t^{(2)} = 0, i_t^{(1)} = 0, \xi_t = 0, \nu_t = \nu\},$$

$$p(i_2, i_1, r, \nu, \eta) =$$

$$\lim_{t \to \infty} P\{i_t^{(2)} = i_2, i_t^{(1)} = i_1,\ \xi_t = r, \nu_t = \nu, \eta_t = \eta\},$$

$$i_1 = \overline{0, R - i_2},\ i_2 = \overline{0, N},\ \nu = \overline{0, W}, \eta = \overline{1, M_r}, r = 1, 2.$$

To simplify operation with the probabilities, we enumerate the states of the processes in the lexicographic order and introduce the vectors of stationary probabilities:

$$\mathbf{p}(0,0,0) = (p(0,0,0,0), p(0,0,0,1), \ldots, p(0,0,0,W)),$$

$$\mathbf{p}(i_2, i_1, r) = (p(i_2, i_1, r, 0, 1), \ldots,$$

$$p(i_2, i_1, r, 0, M_r), p(i_2, i_1, r, 1, 0), \ldots,$$

$$p(i_2, i_1, r, 1, M_r), \ldots, p(i_2, i_1, r, W, M_r)),\ r = 1, 2.$$

So, the row vector $\mathbf{p}(0,0,0)$ has dimension $\bar{W}$, the row vector $\mathbf{p}(i_2, i_1, r)$ has dimension $\bar{W} M_r$, $r = 1, 2$.

In what follows, we use the following denotations: $I.$ is the indentity matrix of dimension defined by the suffix, $\mathbf{0}$ is the row vector of dimension which should be clear from context, $\otimes$ and $\oplus$ are the symbols of Kronecker product and sum of the matrices correspondingly, $\delta_{i,j}$ is Kronecker delta: $\begin{cases} 1, & if\, i = j, \\ 0, & if\, i \ne j. \end{cases}$

Theorem 1. *The vectors* $\mathbf{p}(0,0,0)$, $\mathbf{p}(i_2, i_1, r)$ *satisfy the following system of equations:*

$$\mathbf{0} = \mathbf{p}(0,0,0) D_0 + \mathbf{p}(0,0,1) I_{\bar{W}} \otimes S_0^{(1)} + \mathbf{p}(0,0,2) I_{\bar{W}} \otimes S_0^{(2)}, \tag{1}$$

$$\mathbf{0}=\mathbf{p}(0,i_1,1)(D_0\oplus S^{(1)})+\mathbf{p}(0,0,0)D_{i_1+1}^{(1)}\otimes\boldsymbol{\beta}_1+$$
$$\sum_{m=0}^{i_1-1}\mathbf{p}(0,m,1)D_{i_1-m}^{(1)}\otimes I_{M_1}+$$
$$+\mathbf{p}(0,i_1+1,1)I_{\bar W}\otimes S_0^{(1)}\boldsymbol{\beta}_1+\mathbf{p}(0,i_1+1,2)I_{\bar W}\otimes S_0^{(2)}\boldsymbol{\beta}_1,$$
$$i_1=\overline{0,R-1}, \tag{2}$$

$$\mathbf{0}=\mathbf{p}(i_2,i_1,1)(D_0\oplus S^{(1)})+\sum_{m=0}^{i_1-1}\mathbf{p}(i_2,m,1)D_{i_1-m}^{(1)}\otimes I_{M_1}+$$
$$+\sum_{m=0}^{i_2-1}\mathbf{p}(m,i_1,1)D_{i_2-m}^{(2)}\otimes I_{M_1},\, i_1=\overline{0,R-i_2-1},$$
$$i_2=\overline{1,N-1}, \tag{3}$$

$$\mathbf{0}=\mathbf{p}(N,i_1,1)((D_0+\hat D_1^{(2)})\oplus S^{(1)})+$$
$$\sum_{m=1}^{i_1-1}\mathbf{p}(N,m,1)(D_{i_1-m}^{(1)}\otimes I_{M_1})+$$
$$+\sum_{i_2=0}^{N-1}\mathbf{p}(i_2,i_1,1)(\hat D_{N-i_2}^{(2)}\otimes I_{M_1}),\, i_1=\overline{0,R-N-1}, \tag{4}$$

$$\mathbf{0}=\mathbf{p}(i_2,R-i_2,1)(D(1)\oplus S^{(1)})+$$
$$\sum_{m=0}^{R-i_2-1}\mathbf{p}(i_2,m,1)(\hat D_{R-i_2-m}^{(1)}\otimes I_{M_1})+$$
$$+\sum_{l=0}^{i_2-1}\mathbf{p}(l,R-i_2,1)(\hat D_{i_2-l}^{(2)}\otimes I_{M_1}),\; i_2=\overline{1,N}, \tag{5}$$

$$\mathbf{0}=\mathbf{p}(0,R,1)(D(1)\oplus S^{(1)})+\mathbf{p}(0,0,0)\hat D_{R+1}^{(1)}\otimes\boldsymbol{\beta}_1+$$
$$\sum_{m=0}^{R-1}\mathbf{p}(0,m,1)(\hat D_{R-m}^{(1)}\otimes I_{M_1}), \tag{6}$$

$$\mathbf{0}=\mathbf{p}(i_2,i_1,2)(D_0\oplus S^{(2)})+$$
$$\sum_{m=0}^{i_1-1}\mathbf{p}(i_2,m,2)(D_{i_1-m}^{(1)}\otimes I_{M_2})+$$
$$+\mathbf{p}(0,0,0)(D_{i_2+1}^{(2)}\otimes\boldsymbol{\beta}_2)\delta_{i_1,0}+$$
$$\sum_{m=0}^{i_2-1}\mathbf{p}(m,i_1,2)(D_{i_2-m}^{(2)}\otimes I_{M_2})+\mathbf{p}(i_2+1,i_1,1)(I_{\bar W}\otimes S_0^{(1)}\boldsymbol{\beta}_2)+$$
$$+\mathbf{p}(i_2+1,i_1,2)(I_{\bar W}\otimes S_0^{(2)}\boldsymbol{\beta}_2),\; i_2=\overline{0,N-1},$$
$$i_1=\overline{0,R-i_2-1}, \tag{7}$$

$$\mathbf{0}=\mathbf{p}(N,i_1,2)((D_0+\hat D_1^{(2)})\oplus S^{(2)})+$$
$$\sum_{m=1}^{i_1-1}\mathbf{p}(N,m,2)(D_{i_1-m}^{(1)}\otimes I_{M_2})+ \tag{8}$$
$$+\sum_{i_2=0}^{N-1}\mathbf{p}(i_2,i_1,2)(\hat D_{N-i_2}^{(2)}\otimes I_{M_2})+$$
$$\mathbf{p}(0,0,0)(\hat D_{N+1}^{(2)}\otimes\boldsymbol{\beta}_2)\delta_{i_1,0},$$
$$i_1=\overline{0,R-N-1},$$

$$\mathbf{0}=\mathbf{p}(i_2,R-i_2,2)(D(1)\oplus S^{(2)})+$$
$$\sum_{m=0}^{R-i_2-1}\mathbf{p}(i_2,m,2)(\hat D_{R-i_2-m}^{(1)}\otimes I_{M_2})+$$
$$+\sum_{l=0}^{i_2-1}\mathbf{p}(l,R-i_2,2)(\hat D_{i_2-l}^{(2)}\otimes I_{M_2}),\; i_2=\overline{0,N}. \tag{9}$$

Proof of the theorem is implemented by means of analysis of intensity of transition of the process $\zeta_t,\ t\geq 0$.

Combine now the states corresponding to a fixed value of components i_2 and r and introduce macro-vectors of stationary probabilities:

$$\tilde{\mathbf{p}}(0)=\mathbf{p}(0,0,0),$$
$$\mathbf{p}(i_2,r)=(\mathbf{p}(i_2,0,r),\mathbf{p}(i_2,1,r),\dots,\mathbf{p}(i_2,R-i_2,r)),$$
$$i_2=\overline{0,N},\ r=1,2.$$

Introduce the following denotations of matrices:

- $\mathcal{B}_i^{(r,r')}$ is the matrix of dimension $(R+1-i)\bar W M_r\times(R+2-i)\bar W M_{r'}$. For $r'=2$, $i=\overline{1,N}$, this matrix represents the block diagonal matrix with diagonal blocks $I_{\bar W}\otimes S_0^{(r)}\boldsymbol{\beta}_2$ supplemented from the right side by the zero block column of dimension $(R+1-i)\bar W M_r\times\bar W M_2$. For $i=0$, $r'=1$, the block matrix $\mathcal{B}_0^{(r,1)}$ represents the block diagonal matrix with R diagonal blocks $I_{\bar W}\otimes S_0^{(r)}\boldsymbol{\beta}_1$ supplemented from the right side by the zero block column of dimension $(R+1)\bar W M_r\times\bar W M_1$ and from above by the zero block row of dimension $\bar W M_r\times(\bar W M_1(R+1))$;
- $\mathcal{D}_{i,i+l}^{(r)}$ is the matrix of dimension $(R+1-i)\bar W M_r\times(R+1-i-l)\bar W M_r$, $l=\overline{1,N-1-i}$, $i=\overline{0,N-1}$, $r=1,2$. It consists of the block diagonal matrix with the diagonal blocks $\{D_l^{(2)}\otimes I_{M_r},\dots,D_l^{(2)}\otimes I_{M_r},\hat D_l^{(2)}\otimes I_{M_r}\}$ supplemented from below by the zero matrix;
- $\mathcal{A}_i^{(r)}$ is the square matrix of dimension $(R-i+1)\bar W M_r$, $i=\overline{0,N-1}$, $r=1,2$, defined as follows:

$$\mathcal{A}_i^{(r)} = \begin{pmatrix} D_0 \oplus S^{(r)} & D_1^{(1)} \otimes I_{M_r} & D_2^{(1)} \otimes I_{M_r} & \dots & D_{R-i-1}^{(1)} \otimes I_{M_r} & \hat{D}_{R-i}^{(1)} \otimes I_{M_r} \\ O & D_0 \oplus S^{(r)} & D_1^{(1)} \otimes I_{M_r} & \dots & D_{R-i-2}^{(1)} \otimes I_{M_r} & \hat{D}_{R-i-1}^{(1)} \otimes I_{M_r} \\ O & O & D_0 \oplus S^{(r)} & \dots & D_{R-i-3}^{(1)} \otimes I_{M_r} & \hat{D}_{R-i-2}^{(1)} \otimes I_{M_r} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ O & O & O & \dots & D_0 \oplus S^{(r)} & \hat{D}_1^{(1)} \otimes I_{M_r} \\ O & O & O & \dots & O & D(1) \oplus S^{(r)} \end{pmatrix}; \quad (10)$$

- $\mathcal{A}_N^{(r)}$ is the square matrix of dimension $(R-N+1)\bar{W}M_r$, $r=1,2$, having the same structure, as the matrix (10), but the matrix D_0 on diagonal blocks is replaced with $D_0 + \hat{D}_1^{(2)}$;

- $\mathcal{D}_{i,N-i}^{(r)}$ has the analogous structure, but the blocks of the diagonal matrix are equal to $\hat{D}_{N-i}^{(2)} \otimes I_{M_r}$;

- $\mathcal{T}^{(r)}$ has dimension $(R+1)\bar{W}M_r \times \bar{W}$ and is defined as the block column having zero blocks except the first block which is equal to $I_{\bar{W}} \otimes S_0^{(r)}$;

- $\mathcal{Z}^{(1)}$ has dimension $\bar{W} \times (M_1(R+1)\bar{W})$ and is defined by

$$\mathcal{Z}^{(1)} = (D_1^{(1)} \otimes \boldsymbol{\beta}_1, \dots, D_R^{(1)} \otimes \boldsymbol{\beta}_1, \hat{D}_{R+1}^{(1)} \otimes \boldsymbol{\beta}_1);$$

- $\mathcal{Z}_l^{(2)}$ has dimension $\bar{W} \times (\bar{W}M_2(R+2-l))$ and is calculated by

$$\mathcal{Z}_l^{(2)} = (D_l^{(2)} \otimes \boldsymbol{\beta}_2, 0, \dots, 0),\ l = \overline{1,N},$$

$$\mathcal{Z}_{N+1}^{(2)} = (\hat{D}_{N+1}^{(2)} \otimes \boldsymbol{\beta}_2, 0, \dots, 0).$$

Corollary 1. The macro-vectors $\tilde{\mathbf{p}}(0)$, $\mathbf{p}(i,r)$, $r=1,2$ satisfy the following system of equations:

$$\mathbf{0} = \tilde{\mathbf{p}}(0)D_0 + \mathbf{p}(0,1)\mathcal{T}^{(1)} + \mathbf{p}(0,2)\mathcal{T}^{(2)}, \quad (11)$$

$$\mathbf{0} = \tilde{\mathbf{p}}(0)\mathcal{Z}^{(1)} + \mathbf{p}(0,1)(\mathcal{A}_0^{(1)} + \mathcal{B}_0^{(1,1)}) + \mathbf{p}(0,2)\mathcal{B}_0^{(2,1)}, \quad (12)$$

$$\mathbf{0} = \mathbf{p}(i,1)\mathcal{A}_i^{(1)} + \sum_{l=0}^{i-1} \mathbf{p}(l,1)\mathcal{D}_{l,i-l}^{(1)},\ i = \overline{1,N}, \quad (13)$$

$$\mathbf{0} = \mathbf{p}(i,2)\mathcal{A}_i^{(2)} + \tilde{\mathbf{p}}(0)\mathcal{Z}_{i+1}^{(2)} + \mathbf{p}(i+1,1)\mathcal{B}_{i+1}^{(1,2)} + \mathbf{p}(i+1,2)\mathcal{B}_{i+1}^{(2,2)} + \sum_{m=0}^{i-1} \mathbf{p}(m,2)\mathcal{D}_{m,i-m}^{(2)},\ i = \overline{1,N-1}, \quad (14)$$

$$\mathbf{0} = \mathbf{p}(N,2)\mathcal{A}_N^{(2)} + \tilde{\mathbf{p}}(0)\mathcal{Z}_{N+1}^{(2)} + \sum_{m=0}^{N-1} \mathbf{p}(m,2)\mathcal{D}_{m,N-m}^{(2)}. \quad (15)$$

Denote

$$\mathbf{p}(i) = (\mathbf{p}(i,1), \mathbf{p}(i,2)),\ i = \overline{0,N},$$

$$\mathbf{p} = (\tilde{\mathbf{p}}(0), \mathbf{p}(0), \mathbf{p}(1), \dots, \mathbf{p}(N)).$$

Corollary 2. The macro-vector $\mathbf{p}$ satisfies equation:

$$\mathbf{p}Q = \mathbf{0} \quad (16)$$

where Q is generator of the Markov chain $\zeta_t, t \geq 0$ having the following structure:

$$Q = \begin{pmatrix} D_0 & \mathcal{Z}_0 & \mathcal{Z}_1 & \mathcal{Z}_2 & \mathcal{Z}_3 & \dots & \mathcal{Z}_N \\ \mathcal{T} & \mathcal{A}_0 & \mathcal{D}_{0,1} & \mathcal{D}_{0,2} & \mathcal{D}_{0,3} & \dots & \mathcal{D}_{0,N} \\ O & \mathcal{B}_1 & \mathcal{A}_1 & \mathcal{D}_{1,1} & \mathcal{D}_{1,2} & \dots & \mathcal{D}_{1,N-1} \\ O & O & \mathcal{B}_2 & \mathcal{A}_2 & \mathcal{D}_{2,1} & \dots & \mathcal{D}_{2,N-2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ O & O & O & O & O & \dots & \mathcal{A}_N \end{pmatrix}, \quad (17)$$

where

$$\mathcal{T} = \begin{pmatrix} \mathcal{T}^{(1)} \\ \mathcal{T}^{(2)} \end{pmatrix},$$

$$\mathcal{A}_0 = \begin{pmatrix} \mathcal{A}_0^{(1)} + \mathcal{B}_0^{(1,1)} & O \\ \mathcal{B}_0^{(2,1)} & \mathcal{A}_0^{(2)} \end{pmatrix},$$

$$\mathcal{A}_i = \mathrm{diag}\{\mathcal{A}_i^{(1)}, \mathcal{A}_i^{(2)}\},\ i = \overline{1,N},$$

$$\mathcal{B}_i = \begin{pmatrix} O & \mathcal{B}_i^{(1,2)} \\ O & \mathcal{B}_i^{(2,2)} \end{pmatrix}, i = \overline{1,N},$$

$$\mathcal{D}_{i,i+l} = \mathrm{diag}\{\mathcal{D}_{i,i+l}^{(1)}, \mathcal{D}_{i,i+l}^{(2)}\}, i = \overline{0,N-1}, l = \overline{1,N-i-1},$$

$$\mathcal{D}_{i,N-i} = \mathrm{diag}\{\mathcal{D}_{i,N-i}^{(1)}, \mathcal{D}_{i,N-i}^{(2)}\}, i = \overline{0,N-1},$$

$$\mathcal{Z}_0 = (\mathcal{Z}^{(1)}, \mathcal{Z}_1^{(2)}),$$

$$\mathcal{Z}_i = (O, \mathcal{Z}_{i+1}^{(2)}), i = \overline{1,N},$$

$\mathrm{diag}\{C_1, \dots, C_N\}$ denotes the block diagonal matrix with the diagonal entries $\{C_1, \dots, C_N\}$.

Direct solution of the system (16) is possible as it is the finite system of linear algebraic equations with normalization condition

$$\tilde{\mathbf{p}}(0)\mathbf{e} + \sum_{i=0}^{N} \mathbf{p}(i)\mathbf{e} = 1. \quad (18)$$

However, the blocking matrix (17) (generator of the process ζ_t, $t \geq 0$) has only non-zero blocks below the sub-diagonal. So, the effective and stable algorithm for solving system (16),(18), which is presented in (Klimenok and Dudin, 2003), (Klimenok and Dudin, 2005), can be applied for solving this system.

Having the stationary distribution of the Markov chain $\zeta_t, t \geq 0$ been computed, different performance measures of the system can be calculated and optimization problems can be solved. In particular, probabilities $P_{loss}^{(l)}$ that the arbitrary type-l customer, $l = 1, 2$ is lost is calculated as given in the following statement.

Theorem 2. *The loss probabilities* $P_{loss}^{(l)}$, $l = 1, 2$ *are calculated by*

$$P_{loss}^{(1)} = \lambda_1^{-1}\Bigg(\mathbf{p}(0,0,0)\sum_{k=R+2}^{\infty}(k-R-1)D_k^{(1)}\mathbf{e}+ \sum_{l=1}^{2}\sum_{i_2=0}^{N}\sum_{i_1=0}^{R-i_2}\mathbf{p}(i_2,i_1,l)\times \sum_{k=R-i_2-i_1+1}^{\infty}(k-R+i_2+i_1)D_k^{(1)}\otimes I_{M_l}\mathbf{e}\Bigg),$$

$$P_{loss}^{(2)} = \lambda_2^{-1}\Bigg(\mathbf{p}(0,0,0)\sum_{k=N+2}^{\infty}(k-N-1)D_k^{(2)}\mathbf{e}+ \sum_{l=1}^{2}\sum_{i_2=0}^{N}\sum_{i_1=0}^{R-i_2}\mathbf{p}(i_2,i_1,l)\times \sum_{k=\min\{N-i_2+1,R-i_2-i_1+1\}}^{\infty}(k-\min\{N-i_2,R-i_2-i_1\})\times D_k^{(2)}\otimes I_{M_l}\mathbf{e}\Bigg).$$

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AUTHOR BIOGRAPHIES

KHALID AL-BEGAIN is Professor Mobile Networking in the School of Computing, University of Glamorgan. He obtained his BSc (86), MSc (88 with Distinction) and PhD degree (89) in Communications Engineering from the Technical University of Budapest Hungary. He has been an associate professor at the Department of Computer Science of Mu'tah University, Jordan. He then paid several research visits several universities in Italy. In 1997, he was awarded the Alexander von Humboldt Research Fellowship at the Department of Computer Science of the University of Erlangen-Nuremberg, Germany, where he established a research group on modelling of mobile networks and contributed to the invention of the Modelling, Specification and Evaluation

Language - MOSEL. He also spent another year as guest professor as the Chair of Telecommunications at Dresden University of Technology supported by SEW-Eurodrive (Bruchsal-Germany) Grant where he led the research projects as part of a research project between the Chair and Lucent Technologies-Nuremberg. He has been an advisor for a modelling project for the research group of Lucent Technologies, Nuremberg/Germany. In 2000, he became the Director of research in the School of Computing of Bradford University in England before taking the chair at Glamorgan in 2003. Prof. Al-Begain is co-author the book Practical Performance Modelling published by Kluwer Academic Publishers in 2001 and more than 100 journal and conference papers. He has been the Guest Editor for several special issues of the international journals. He is UNESCO Expert in networking, UK Representative to EU COST Action 290 Management Committee on Traffic and QoS management of Wireless Multimedia Networks, Senior Member of the IEEE, Fellow and Charter IT Professional of the British Computer Society, Wales Representative to IEEE UKRI Computer Chapter Steering Committee and many other scientific organisations. Since 2003, he became the Conference Chair for the annual ASMTA (Analytical and Stochastic Modelling Techniques and Applications) Conference (ASMTA'03 in Nottingham, and ASMTA'04 in Magdeburg, Germany, ASMTA05 in Riga, Latvia). He also the Co-Chair of PMW2MN05 held in Japan in July 2005. He will be the General Chair for the IEEE HSNMC07 Conference to be hosted in Glamorgan.

ALEXANDER N. DUDIN has got Master degree in Applied Mathematics in 1976 from Belarusian State University, PhD - degree in 1982 from Vilnius University (now Lithuania) and 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, Glamorgan University (UK), 2005. Currently he is the Head of the Laboratory of Applied Probabilistic Analysis in Belarusian State University, Professor of the Probability Theory and Mathematical Statistics Department. He is the Chairman of Organizing Committee of Belarusian Winter Workshops in Queueing Theory. Fields of scientific interests: stochastic processes, queues (controlled queues and queues in random environment, in particular) and their applications in telecommunications, databases, etc.

VILENA V. MUSHKO currently is the second year PhD -student of the Department of Applied Mathematics and Computer Science in Belarusian State University. Her current field of scientific interests is queueing theory and its applications.