Methods of Performance Evaluation of Broadband Wireless Networks Along the Long Transport Routes

Vladimir Vishnevsky[1], Alexander Dudin[2], Dmitry Kozyrev[1,3(✉)], and Andrey Larionov[1]

[1] V.A. Trapeznikov Institute of Control Sciences of Russian Academy of Sciences, Moscow, Russia
vishn@inbox.ru, kozyrevdv@gmail.com, larioandr@gmail.com
[2] Belarusian State University, Minsk, Belarus
dudin@bsu.by
[3] Peoples' Friendship University of Russia, Moscow, Russia

Abstract. This paper presents the description of the method of performance evaluation and assessment of main characteristics of broadband wireless networks with linear topology, which is based on a model of stochastic multiphase queueing systems with correlated MAP input flows and a cross-traffic. The results of analytical calculations for the networks of small dimension are given. A simulation model for assessment of performance characteristics of large-scale wireless networks with linear topology is developed.

Keywords: Wireless networks · Stochastic multi-stage systems · Markov arrival process · Performance evaluation · Analytical modeling and simulation

1 Introduction

One of the major problems in the development of new and operation of existing transport routes (railroads, highways, gas and oil pipes) is the creation of a modern wireless communication infrastructure based on the international IEEE 802.11–2012 standard [1]. This standard regulates the creation of high-speed communication channels and wireless networks that operate under the control of IEEE 802.11n and IEEE 802.11s protocols, on the basis of which one can effectively implement the wireless networks along the long transport routes. These networks can provide not only the backbone for high-speed transmission of multimedia information by deploying the base stations on high-rise buildings and towers along the transport routes, but also an operation communication between the fixed and mobile users (cars, trains, road signs, weight control points and transport security control points, traffic lights control points, etc.) as well [2,3].

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The deployment and development of wireless networks along extended routes requires solving a number of complex organizational and technical tasks under tight restrictions on the use of frequency, economic, and hardware resources. In this regard, it seems to be increasingly urgent to solve the problem of optimal allocation of base stations along the long transport routes, which is one of the most important problems in designing the broadband wireless networks of this class. Its solution is aimed both at the realization of high speed backbone network and at the maximum network coverage of the route to provide connectivity for mobile users, as well as to minimize interference and time delays when transmitting the multimedia data over the network. Numerous papers are devoted to the solution of this problem [4–8,10,12].

In current paper we present a new approach to performance evaluation of wireless networks with linear topology based on the model of stochastic multistage system with a Markov arrival process (MAP) and a cross-traffic. This paper is the development of studies initiated in [9,11], with regard to the development of effective computational algorithms and conduction of simulations that enable to evaluate the performance characteristics of large-scale networks.

2 Description of the Model of a Wireless Network with a Linear Topology

A broadband wireless network along the long transport routes is a set of base stations, connected with each other with high-speed wireless communication channels. An adequate mathematical model for such a network is a multi-stage queueing system with a MAP input flow, PH-distribution of service time at the stages of the system and a cross-traffic (Fig. 1).

The term "service" of each message refers to a number of technical processes in a real network, the duration of which is a random variable. Thus the messages are processed by one or several program components and the processing time depends on the current load of the central processing unit (CPU) and the memory of a base station, on the number of concurrently served messages, the number of CPU cores and other parameters. The messages then come to the output device and are transmitted through the network over one or more serial communication channels to the next base station. The transmission time via communication channels is also a random variable, since it is influenced by the background traffic, the implemented networking technologies, the setup of traffic profiling, and many other factors.

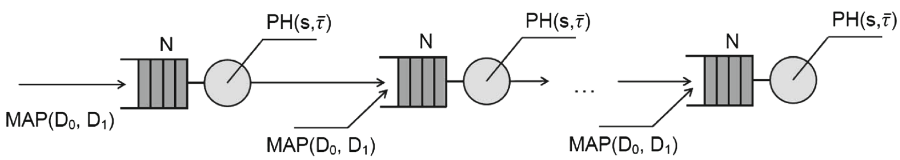

Fig. 1. Tandem queueing model

In general case, such processing time should be modeled by PH-distributions: each phase corresponds to a certain technical process (processing by software component, transmission through communication lines). PH-distribution is described by a continuous-time Markov chain with $M+1$ states in which the zero state is ‘’absorbing” - after arriving to this state a message is considered to be processed. Denote by $PH(\overline{\tau},\ S)$ the phase-type distribution of time till absorption at the 0 phase in a continuous-time Markov chain with a discrete state space $\{0, 1, \dots, M\}$, steady-state distribution $(\tau_0, \overline{\tau})$, where $\tau_0 = 1 - \overline{\tau}\overline{\mathbf{1}}_M$, and infinitesimal generator T:

$$T = \begin{pmatrix} 0 & 0 \\ -S\overline{\mathbf{1}}_M & S \end{pmatrix},\ S \in \mathbb{R}^{M \times M}$$

$$\overline{\mathbf{1}}_M = [1\ \dots\ 1]^T \in \mathbb{R}^{M \times 1}$$

Each base station of the wireless network transmits not only messages from the previous base station, but the messages from mobile users as well (the cross-traffic). We assume that the input flows of messages and the cross-traffic flow are MAP-flows, which allows to take into account the complex and correlated nature of data flows in wireless communication networks.

In the Markov chain, which controls the MAP, all transitions are divided into observable and hidden. When an observable transition occurs, the arrival process generates a package and, if the initial and the final states differ, then the change of states occurs. Under a hidden transition only the change of states is done. Hidden and observable transition rates are represented by the matrices D_0 and D_1 respectively:

$$D_0 = \begin{cases} \lambda_{ij}^{(0)},\ i \neq j \\ -\lambda_i,\ i = j \end{cases}, \quad i,\ j = \overline{1, W}$$

$$D_1 = \left\{ \lambda_{ij}^{(1)} \right\},\ i,\ j = \overline{1, W}$$

$$\lambda_i = \lambda_{ii}^{(1)} + \sum_{\substack{j=1 \\ j \neq i}}^{W} \left(\lambda_{ij}^{(0)} + \lambda_{ij}^{(1)} \right)$$

where $\lambda_{ij}^{(0)}$ — hidden transition rates, $\lambda_{ij}^{(1)}$ — observable transition rates, and λ_i — total rate of leaving a state or generation of a message without changing the state. The sum of matrices D_0 and D_1 is the infinitesimal generator of the Markov chain:

$$D = D_0 + D_1$$

An elementary check, considering the definition of λ_i, shows that the sum of all elements for each row of the generator D is equal to zero.

Stationary probabilities $\overline{\theta} \in \mathbb{R}^W$ of the Markov process are calculated from the balance equations and the normalization condition:

$$\begin{cases} \overline{\theta} D &= \overline{\mathbf{0}}_W \\ \overline{\theta} \overline{\mathbf{1}}_W &= 1 \end{cases} \tag{1}$$

where $\overline{\mathbf{0}}_W = \left\| 0\ 0\ \dots\ 0 \right\| \in \mathbb{R}^W$ — row vector of zeros and $\overline{\mathbf{1}}_W = \left\| 1\ 1\ \dots\ 1 \right\|^T \in \mathbb{R}^W$ — column vector of ones. Using the obtained stationary probability distribution, we can calculate the average rate of messages, generated by the MAP-flow, as a mean value of a random variable equal to a cumulative rate of observable transitions from the specified state:

$$\lambda = \sum_{i=0}^{W} \left[\theta_i \sum_{j=0}^{W} \lambda_{ij}^{(1)} \right] = \overline{\theta} D_1 \overline{\mathbf{1}}_W \tag{2}$$

Since the base stations of the wireless network have buffers of limited capacity, it is necessary to take into consideration in the mathematical model the restrictions on queue lengths at servers of each stage.

As the result, a multi-stage queuing system $MAP/PH/1/N \rightarrow \bullet/PH/1/N \rightarrow \cdots \rightarrow \bullet/PH/1/N$ is described, which adequately describes the functioning of a broadband wireless network with a linear topology.

3 Properties and Characteristics of a *MAP/PH/1/N* System

Before proceeding to calculation of the stationary characteristics of a $MAP/PH/1/N$ system, we formulate the following two theorems:

Theorem 1. *Let the input flow* $X = MAP(D_0^{(X)}, D_1^{(X)})$, $D_0^{(X)},\ D_1^{(X)} \in \mathbb{R}^{W \times W}$ *arrive at the system MAP/PH/1/N, and let the service time has a phase-type distribution* $Y = PH(S, \overline{\tau})$, $S \in \mathbb{R}^{M \times M}, \overline{\tau} \in \mathbb{R}^{1 \times M}$. *Then the output flow of the system will be a MAP flow* $Z = MAP(D_0^{(Z)}, D_1^{(Z)})$, *which transition rate matrices* $D_{0,1}^{(Z)} \in \mathbb{R}^{(WM(N+2)) \times (WM(N+2))}$ *have forms:*

$$D_0^{(Z)} = \begin{pmatrix} \tilde{D}_0 & B_1 & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & R_0 & \tilde{D}_1 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & R_0 & \tilde{D}_1 & \dots & 0 & 0 & 0 \\ 0 & 0 & 0 & R_0 & \dots & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & 0 & \dots & R_0 & \tilde{D}_1 & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 & R_0 & \tilde{D}_1 \\ 0 & 0 & 0 & 0 & \dots & 0 & 0 & R_A \end{pmatrix} \tag{3}$$

$$D_1^{(Z)} = \begin{pmatrix} 0 & \dots & 0 & 0 & 0 \\ I_W \otimes C_t & \dots & 0 & 0 & 0 \\ 0 & \dots & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & I_W \otimes C_t & 0 & 0 \\ 0 & \dots & 0 & I_W \otimes C_t & 0 \end{pmatrix}$$

where matrices $\tilde{D}_0$, $\tilde{D}_1$ B_1, R_0, R_A, C_t *are defined as follows:*

$$\begin{aligned}
\tilde{D}_0 &= D_0 \otimes I_M \\
\tilde{D}_1 &= D_1 \otimes I_M \\
B_1 &= D_1 \otimes \left(\overline{\tau} \otimes \overline{\mathbf{1}}_M\right) \\
R_0 &= D_0 \otimes I_M + I_W \otimes S - I_W \otimes C_t \\
R_A &= (D_0 + D_1) \otimes I_M + I_W \otimes S - I_W \otimes C_t \\
C_t &= \begin{bmatrix} \mu_{10} \\ \mu_{20} \\ \dots \\ \mu_{M0} \end{bmatrix} \otimes \overline{\tau} = (-S\overline{\mathbf{1}}_M) \otimes \overline{\tau}
\end{aligned} \tag{4}$$

From now on $A \otimes B$ — is a Kronecker product of matrices A and B, and $I_K \in \mathbb{R}^{K \times K}$ — is an identity matrix of order K.

Thus, the given theorem states, that the output flow of the queuing system MAP/PH/1/N is again a MAP-flow.

Taking into account, that at each stage of the multi-stage system both a MAP flow and a cross traffic from the previous stage arrive, we can prove the following theorem:

Taking into account that at each station (phase) of the multi-stage system both a MAP flow from the previous station and a cross-traffic flow arrive, then the following theorem can be proved:

Theorem 2. *Composition of MAP-flows X and Y with transition rate matrices* $D_0^{(X)}$, $D_1^{(X)} \in \mathbb{R}^{M \times M}$ $D_0^{(Y)}$, $D_1^{(Y)} \in \mathbb{R}^{N \times N}$ *is a MAP-flow* $Z = X \otimes Y$*, which transition rate matrices* $D_0^{(Z)}$, $D_1^{(Z)} \in \mathbb{R}^{(MN) \times (MN)}$ *are defined as follows:*

$$\begin{aligned}
D_0^{(Z)} &= I_N \otimes D_0^{(X)} + D_0^{(Y)} \otimes I_M \\
D_1^{(Z)} &= I_N \otimes D_1^{(X)} + D_1^{(Y)} \otimes I_M
\end{aligned} \tag{5}$$

Thus, the given theorem states, that a composition of two MAPs is again a MAP.

The formulated above theorems are used to calculate the performance characteristics of a multi-stage queuing system.

Further let's consider a method for computation of steady-state probability distribution. The stationary probabilities will allow to find the loss probability, the message arrival rates, the marginal distributions of queue lengths and other characteristics of the $MAP/PH/1/N$ system.

The steady-state probability distribution $\overline{\theta} \in \mathbb{R}^L$ for the output MAP flow is the solution of the system of linear algebraic equations:

$$\begin{cases} \overline{\theta} D^{(o)} &= \overline{\mathbf{0}}_L \\ \overline{\theta}\overline{\mathbf{1}}_L &= 1 \end{cases} \tag{6}$$

Denote by W a number of states of the input MAP-flow; let M denote a number of nonabsorbing states of the Markov chain that defines the PH-distribution, and let N denote the queue capacity of a server.

For the sake of convenience let as suppose that $\overline{\theta} = \left(\overline{\theta}_0 \dots \overline{\theta}_{N+1}\right)$, where each vector $\overline{\theta}_i \in \mathbb{R}^{WM}$ is a vector of components of distribution corresponding to a state i, i.e. when there i customers in the system.

Let $\eta \in \mathbb{R}^{N+2}$ denote a probability distribution of the number of customers in the system. We can obtain the value of $\eta_n, n = \overline{0, N+1}$ from the vector $\overline{\theta}$:

$$\eta_n = \sum_i \overline{\theta}_{n,i} \tag{7}$$

Given matrices D_0, D_1, D of the input MAP-flow we can get the steady-state distribution $\overline{\phi} \in \mathbb{R}^W$ of the input MAP-flow by solving the following linear algebraic system:

$$\begin{cases} \overline{\phi} D & = \overline{\mathbf{0}}_W \\ \overline{\phi} \mathbf{1}_W & = 1 \end{cases} \tag{8}$$

The obtained steady-state distribution allows to find the following characteristics:

- the average arrival rate of messages into the system λ_{avg}:

$$\lambda_{avg} = \overline{\phi} D_1 \overline{\mathbf{1}}_{W+1} \tag{9}$$

- the average number N_{avg} of messages in the system, which is defined as the expected value of a random variable n:

$$N_{avg} = \sum_{n=0}^{N+1} \eta_n n \tag{10}$$

- and the loss probability P_{loss} of a message arrived at the server:

$$P_{loss} = \overline{\theta}_{N+1} \frac{D_1}{\lambda_{avg}} \overline{\mathbf{1}}_{W+1} \tag{11}$$

4 Calculation of the Performance Parameters of a Multi-stage System $MAP/PH/1/N \to \bullet/PH/1/N \to \dots \to \bullet/PH/1/N$

In the previous section we described the construction of a MAP flow of customers arriving at an i-th stage and gave formulae for calculation of different characteristics of a $MAP/PH/1/N$ system.

The customer arriving to the system under study has to get sequentially the service at all stations of the tandem. However, due to lack of waiting area at the stations the customer can be lost at each of them. So, the quality of a service in the system is essentially defined be the probability of successful service of an arbitrary customer arriving at the tandem by all stations. Also, the probability of losses at different stations and subsystems of a tandem are important for performance evaluation of a tandem network and discovering and avoiding the so called bottlenecks in the network.

The algorithm 1 below (in a form of pseudocode) allows to use the obtained for $MAP/PH/1/N$ formulae to calculate the steady-state loss probabilities, arrival rates and average queue lengths for each station.

Let K denote the number of stations, $\Psi_0 = MAP\,(A_0, A_1)$ – the flow of cross-taffic arriving at each station, $\Phi_i = MAP\left(B_0^{(i)}, B_1^{(i)}\right)$ – the disposal flow from i–th station, $\Psi_i = MAP\left(A_0^{(i)}, A_1^{(i)}\right)$ – arrival flow into the i-th station, $1 \le i \le K$. Let the service at each station follow the PH-distribution $\Omega = PH\,(\overline{\tau},\ S)$.

On account of Theorem 2 we can state that:

$$\begin{aligned} \Psi_1 &= \Psi_0 \\ \Psi_i &= \Phi_{i-1} \otimes \Psi_0,\ 2 \le i \le K \end{aligned} \tag{12}$$

Data: K — number of stations, N — length size, $\Psi_0 = MAP\,(A_0, A_1)$ — cross traffic, $\Omega = PH\,(\overline{\tau},\ S)$ — service time distribution
Result: $P_{loss}^{(i)}$ — probability of message loss at the i-th station,
$\lambda^{(i)}$ — average arrival rate at the i-th station,
$N_{avg}^{(i)}$ — mean number of messages at the i-th station

$i := 1$;
while $i \le K$ **do**
  if $i = 1$ **then**
    $A_0^{(i)} := A_0,\ A_1^{(i)} := A_1$;
  else
    /* $\Psi_i = \Phi_{i-1} \otimes \Psi_0$ */
    calculate $A_0^{(i)}, A_1^{(i)}$ using (5) from $\Psi_0 = MAP\,(A_0, A_1)$
    $\Phi_i = MAP\left(B_0^{(i)}, B_1^{(i)}\right)$;
  end
  calculate $\Phi_i = MAP(B_0^{(i)}, B_1^{(i)})$ using (3);
  using (1) calculate $\overline{\pi}^{(i)} = \left(\overline{\pi}_0^{(i)}, \dots, \overline{\pi}_{N+1}^{(i)}\right)$ – steady-state probabilities of the flow Φ_i;
  using (1) calculate $\overline{\alpha}^{(i)}$ – steady-state probabilities of the flow Ψ_i;
  calculate $\lambda^{(i)}$, using vector $\overline{\alpha}$, in accordance with (9);
  calculate $N_{avg}^{(i)}$, using vector $\overline{\pi}$, in accordance with (10);
  calculate $P_{loss}^{(i)}$, using vector $\overline{\pi}$, in accordance with (11);
  $i := i + 1$;
end

Algorithm 1. Algorithm for calculating the parameters of a tandem system

According to the proposed algorithm, a software bundle was developed for calculation of the key performance characteristics of a wireless network. The main difficulty arising while calculating the parameters of the $MAP/PH/1/N \to \bullet/PH/1/N \to \cdots \to \bullet/PH/1/N$ system is the huge size of matrices describing the MAP-flows, arriving at an i-th station, $i = \overline{1,k}$. Their size grows exponentially, therefore a simulation model was developed for solving the high-dimension issues. The developed software allows to obtain an exact analytical solution for a tandem queue with a small number of stations and MAP with matrices of small dimension. This exact solution is used to tune up the simulation model.

5 Comparison of Results of Analytical Modeling and Simulation

Due to the enormously large matrices even in case of MAPs with 3 states and PH-distribution of service time with 2 phases, the exact solution was obtained for the following two cases:

(1) simple tandem system $M/M/1/N \to \bullet/M/1/N \to \cdots \to \bullet/M/1/N$ with Poisson cross-traffic
(2) system with a MAP input with 2 states $MAP/M/1/N \to \bullet/M/1/N \to \cdots \to \bullet/M/1/N$, where arrival rates were defined by matrices:

$$D_0 = \begin{pmatrix} -1 & 1 \\ 0 & -1 \end{pmatrix},\ D_1 = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix},$$

that corresponds to Erlang distribution with 2 phases and arrival rates equal to 1, service rates equal to 2, queue length $N = 2$, number of stations $K = 4$.

Parameters of the MAP were obtained from the compilation of real data, gathered on Moscow road traffic routes at different times of day.

The Fig. 2 shows the probability density function of time intervals between vehicles, obtained from the collected data and the probability density function of the MAP with following matrices:

$$D_0 = \begin{pmatrix} -0.85 & 0.85 & 0.0 \\ 0.0 & -1.1 & 0.2 \\ 0.0 & 0.5 & -4.0 \end{pmatrix},\ D_1 = \begin{pmatrix} 0.0 & 0.0 & 0.0 \\ 0.9 & 0.0 & 0.0 \\ 3.5 & 0.0 & 0.0 \end{pmatrix}$$

The MAP fits the statistical data on the first two moments.

For both cases P_{loss} (loss probability at each server) and P_{busy} (probability that a server is busy) were found using both simulation and exact analytical calculation.

The comparison results are given in the Table 1.

It can be seen from the table that the results of analytical modelling and simulation have close agreement.

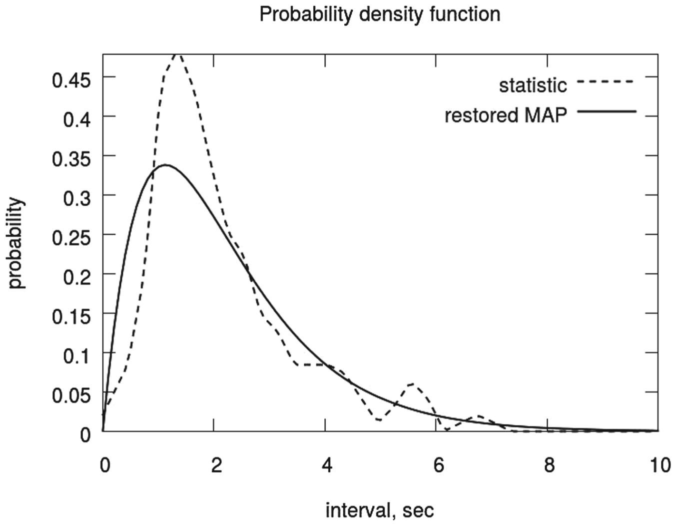

Fig. 2. Probability density functions of intervals (MAP and statistical distribution)

Table 1. Comparison of system characteristics: P_{loss}^{sim} and $P_{loss}^{analytic}$ – stationary loss probabilities, obtained from simulation and analytical models; P_{busy}^{sim} and $P_{busy}^{analytic}$ – stationary probabilities that the server is busy.

Number of station	P_{loss}^{sim}	$P_{loss}^{analytic}$	P_{busy}^{sim}	$P_{busy}^{analytic}$
1	0.0018	0.0019	0.2503	0.2495
2	0.0363	0.0365	0.4813	0.4813
3	0.1138	0.1139	0.6469	0.6480
4	0.1797	0.1815	0.7336	0.7350

6 Calculation of the Performance Characteristics of a Large-Scale Broadband Network

Unlike the analytical approach, simulation allows to obtain the results for a tandem system $MAP/PH/1/N \to \bullet/PH/1/N \to \cdots \to \bullet/PH/1/N$ with a cross traffic for the case of a large number of stages (stations). All the input flows were described by MAP, with matrices given above. The number of stations in the tandem queue equals $Q = 20$ and the maximum queue length $N = 10$. Such restrictions are met in real life when a distributed system operates on basis of very weak embedded platforms — the program components have buffers of limited capacity and the new messages are dropped when buffers overflow. In case of a small amount of available memory the size of buffers of some applications may be limited to 20 messages.

The service procedure was modeled with the use of exponential distributions with different intensities. We considered the following cases:

$$\mu \in \{2, 5, 10, 20, 100, 1000\},$$

starting from the case of high performance hardware and network ($\mu = 1000$) and proceeding to the case of a very weak hardware and low-performance network ($\mu = 2$). The last case appears to be relevant for the reason that under condition of poor communication channels between stations and in case of often downtimes, the average daily rate of service degrades significantly.

Figure 3 shows the average end-to-end delay for each station. The horizontal axis depicts the number of a station that performs the first transition of a message. The vertical axis depicts the stationary average time till this message leaves the system (when served at the last station). The figure shows that starting from $\mu = 100$ the delay doesn't exceed 200 ms. But if $\mu = 20$ it takes about 1.4 s to transfer a message from the most descend station.

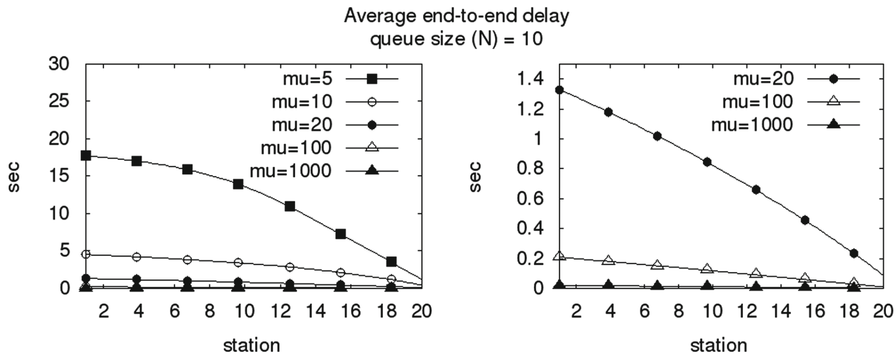

Fig. 3. Stationary average end-to-end delay

Figure 4 shows the average message loss ratio for each station. As it can be seen from this figure, there are almost no losses starting from $\mu = 20$. However, due to the random nature of traffic, it is preferable to have a higher performance in case of a large number of consequent stations.

Figure 5 shows the stationary non-delivery ratio of messages, sent by a specified station on their way to the last station. It is evident, that this value is a non-increasing function of a station number, and starting from $\mu = 20$ it is equal to zero nearly everywhere.

Figure 6 shows the average queue length for each station. For the reason that there additionally arrives a cross-traffic flow at each station, the arrival rate does not decrease as the station number increases. And as all servers have the same rate of service, the average queue length turns out to be a non-decreasing function of the station's number. As it can be seen from the figure, the higher is the service rate, the later the queue gets filed up. Particularly, in case $\mu = 20$ the queue of each station remains empty most of the time.

Finally, Figs. 7 and 8 illustrate the distributions of service delays at each station and distributions of time intervals between the outgoing messages at

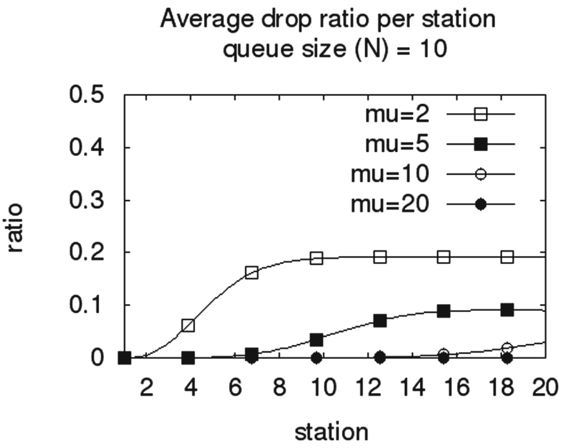

Fig. 4. Stationary loss ratio for each station

each station. The figures are given for different service rates and several stations. In particular, Fig. 8 displays that starting from a certain stage, which depends on the service rate, the output flows become almost indistinguishable.

It is evident, that at a low rate of service the system deteriorates very fast. It is connected mostly with the presence of cross-traffic: each consequent base station has not only to process the messages from the previous station, but the cross-traffic messages as well.

Particularly, the results show that for the high system performance it is necessary to pay attention to the quality of communication links between base stations. For a stable work the average rate of service should be not less than 20 messages per second. The rate of about 100 messages per second is desirable.

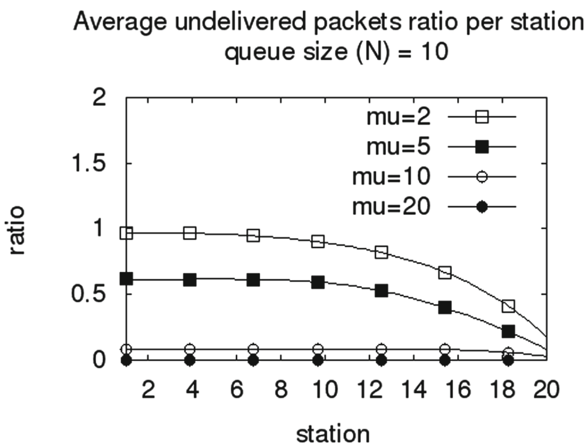

Fig. 5. Stationary non-delivery ratio

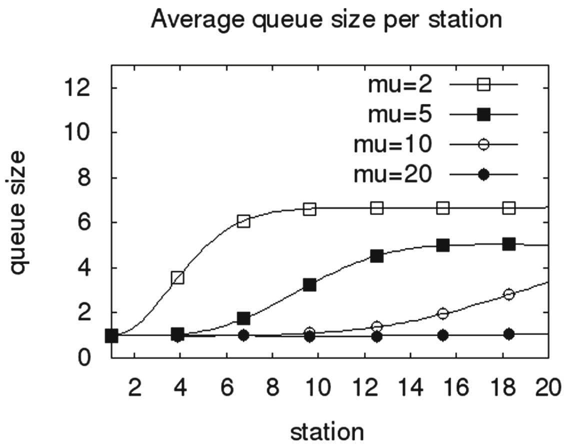

Fig. 6. Average queue length per station

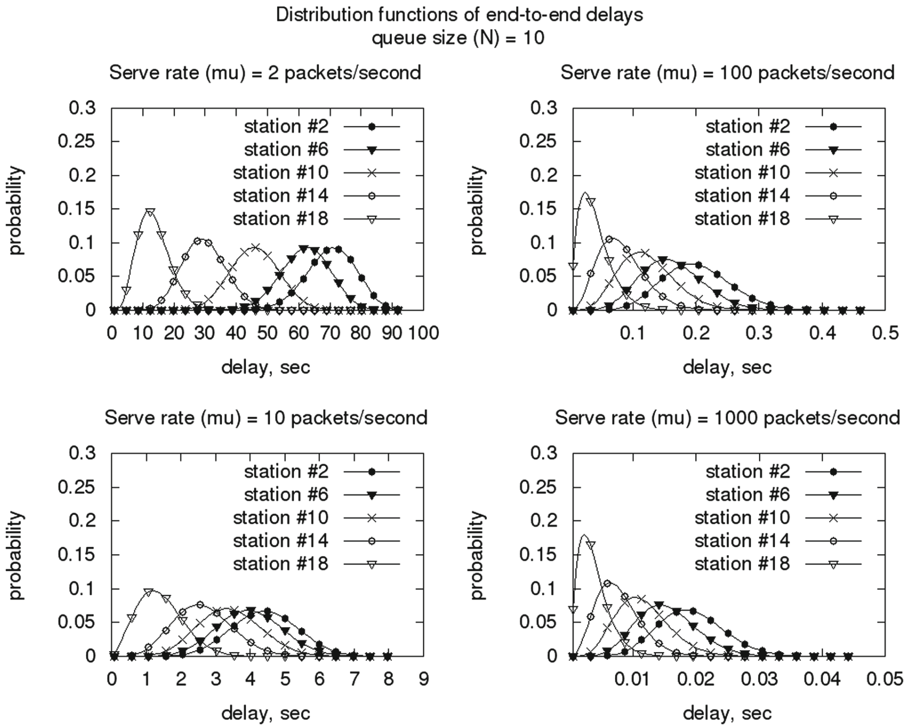

Fig. 7. Distribution density functions of end-to-end delays

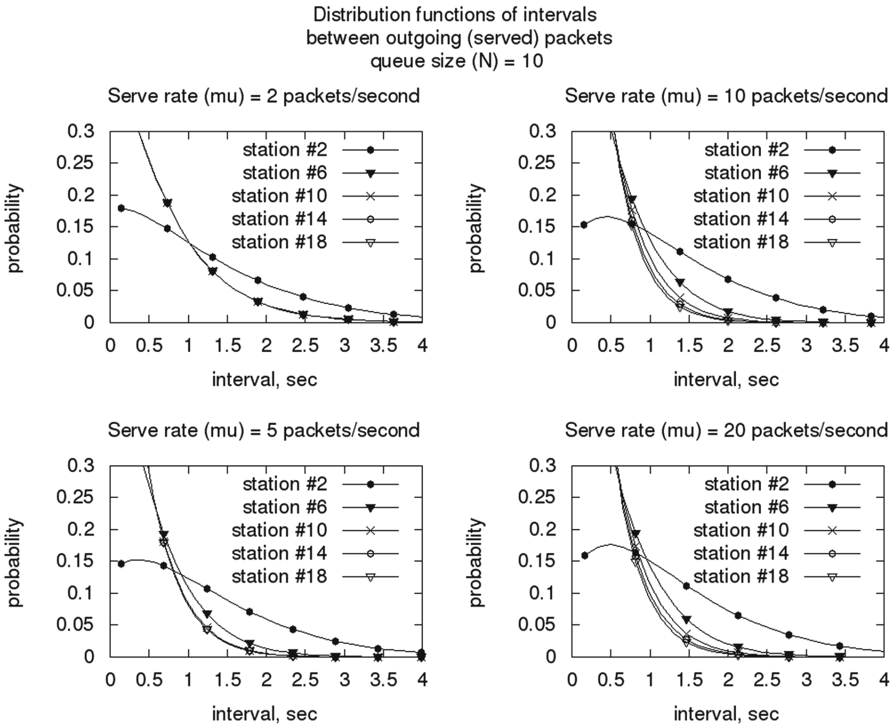

Fig. 8. Distribution density functions of time intervals between served messages

7 Summary

A novel approach was developed to evaluation of key characteristics of multi-stage (tandem) $MAP/PH/1/N \to \bullet/PH/1/N \to \cdots \to \bullet/PH/1/N$ queuing systems with a MAP input, a cross-traffic and PH-distributed service times.

Most of studies devoted to tandem queues are limited to the case of dual tandem queues, i.e. queues consisting of exactly two sequential servers with the stationary Poisson arrival process of customers. In our paper(s) we consider a tandem system, consisting of any finite number of stations with the MAP. The assumption that the arrival process of customers is defined by the MAP instead of stationary Poisson arrival process allows to adequately take into account the complexity and variance and correlated nature of inter-arrival times, typical for information flows in modern wireless communication networks.

We present an algorithm and a corresponding software package for exact calculation of the main performance characteristics of wireless networks of small dimension. For the large-scale case a simulation model was developed and the comparison of analytic and simulation results was carried out. The developed methods were successfully used in the process of design and implementation of a wireless broadband network along the city ring road of Kazan (M7 Volga route), Tatarstan, Russia.

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