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# Study of the Impact of Self-Similarity on the Network Node Traffic

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## Introduction

Numerous network traffic research works [1–3] show that Ethernet networks traffic characteristics have fractal and self-similarity properties with a long-range dependence. The research of self-similarity of networks [1, 3, 4] allows us to predict a change in the flow and to ensure the service's quality [5–6]. The empirical research of university e-studies network traffic confirmed its self-similarity property. The analysis of e-studies network has shown that overflows often occur in it [8].

[9] have found that, in the high network traffic, LIFO front drop (when the queue is full for a longer time, former applications are eliminated and new applications are taken) has a more than twice shorter delay than the FIFO tail drop (when the queue is full, new applications are eliminated). [10–12] analysed the optimal queue length. It has been found that the node services with high-speed (about 30 Gb/s) and throughput networks are enough for the 15-20 data packets' queue.

It should be noted that there is no exhaustive research pursuing to estimate the impact of the queue discipline and network traffic properties on the network node traffic service. This research focuses on design of appropriate network node parameters when network traffic is self-similar.

## Theoretical justification of the network model

The quality of service (QoS) has two components: performance assurance and service differentiation [13]. The component performance assurance directly relates with a bandwidth which affects delay, jitter and packet loss. Our aims are to establish conditions when application's delay and loss are minimal, by analysing the network traffic properties and node parameters and evaluating the offered traffic jitter and service system's throughput. In this article, we do not analyse service differentiation by applying different service requirements to different services.

The network model's investigation is based on a stochastic Network Calculus which allows us to analyse end-to-end network QoS systems with a stochastic network traffic and stochastic network nodes. The deterministic network services' theory has been created by Cruz, Chang, Boudec, Thiran and others [14–16]. This theory was extended in 2008 by Jiang and Liu who wrote a book where stochastic offered and served traffic characteristics are analysed [17].

Our system uses the communication network model for generalised stochastically bounded bursty traffic created by J. Jiang, Q. Yin, Y. Liu and S. Jiang [18]. In this model, both offered and served traffics are independent and stochastic, the network node buffer capacity is determined and finite, the network node is ready for service for the next application when the buffer is empty and the network node doesn't serve any other data packet. The network gets started at time t=0. The network traffic amount arriving in the time interval (s,t] is $A(s,t)=\sum_{i=s+1}^{t} a(i)$. We use $A(t)$ to represent $A(0,t)$. The $a(t)$ describes the obtained traffic at (t-1,t] time, i.e., $a(t)=A(t)-A(t-1)$. The network node flow function $\hat{A}$ is described: $\hat{A}(t;\rho)=\sup_{s\le t}\{A(s,t)-(t-s)\rho\}$, where $\rho$ is offered traffic. In the multichannel service system $\rho=\lambda/\mu$, where $\lambda$ is intensity offered to the system packets, and $\mu$ is intensity of packets transmission through channels.

Traffic is modelled with a generalised stochastically bounded burstiness (gSBB) in a modelling network [18]. For all $t\ge 0$ and all $x\ge 0$ this traffic satisfies the inequality $P\{\hat{A}(t,\rho)>x\}\le f(x)$, where ρ is a higher traffic bound, $f$ is a bounding function which is not increasing and $f(x)\ge 0$ for all $x\ge 0$ [18]. If the gSBB network traffic is stationary and ergodic, then it is proved that $P\{\hat{A}(t;\rho)>x\}$ is always upper bounded by the steady-state queue length distribution, i.e., $P\{\hat{A}(\infty;\rho)>x\}$ in a virtual one-channel system with stable $\rho$. Here $\hat{A}(\infty;\rho)$ denotes a limit $\hat{A}(t;\rho)$, where $t\to\infty$ [18]. The simulated network packets length is variable and satisfies the Ethernet standard requirements.

Min-plus or max-plus algebras can be used for analytical description network systems. Packet losses take place in a stochastic computer network with gSBB traffic which causes its retranslation. Thus, the content-based service takes place and the network traffic is multi-access in this network. Analytical description of the min-plus algebra is inappropriate for this model because the process analysis is based on the cumulative virtual service time. Thus, further analysis is based on max-plus algebra tools. In this algebra $\varepsilon \overset{def}{=} -\infty$ describes the unreachable state, $R$ is the set of real numbers, $R_{\max} = R \cup \{\varepsilon\}$ is a max-plus algebra sample and functions *f* and *g* are described, where $f, g \in R_{\max}$. The operators, used in this algebra, are described as follows [19]:

$\otimes$ is a convolution operator, i.e. convolution of two functions $f$ and $g$ computed by the formula $f \otimes g(t) \equiv \sup_{0 \le s \le t} \{f(s) + g(t-s)\}$;

$\oplus$ is a deconvolution operator, i.e. deconvolution of two functions $f$ and $g$ computed by the formula $f \oplus g(t) \equiv \inf_{s \ge 0} \{f(t+s) - g(s)\}$.

Let $A(k)$ be stationary and ergodic. Denote the time of the $k^{th}$ packet service at channel $j$ by $x_j(k)$, when $t \ge 0$. The service beginning of the $k^{th}$ packet in the channel *j* is denoted by $\sigma_j(k)$. Let the system be open and have *m=10* channels. The evolution of the modelling system can be described by the *j+1* length vector $x(k) = (x_0(k), ..., x_j(k))$ and the next homogeneous equation $x(k+1) = A(k) \otimes x(k)$ [20]. The matrix $A(k-1)$ is described as follows:

$$\begin{pmatrix} \sigma_0(k) & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon \\ \varepsilon & \sigma_1(k) & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon \\ \varepsilon & \varepsilon & \sigma_2(k) & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon \\ \varepsilon & \varepsilon & \varepsilon & \sigma_3(k) & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon \\ \varepsilon & \varepsilon & \varepsilon & \varepsilon & \sigma_4(k) & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon \\ \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \sigma_5(k) & \varepsilon & \varepsilon & \varepsilon & \varepsilon \\ \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \sigma_6(k) & \varepsilon & \varepsilon & \varepsilon \\ \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \sigma_7(k) & \varepsilon & \varepsilon \\ \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \sigma_8(k) & \varepsilon \\ \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \varepsilon & \sigma_9(k) \end{pmatrix}. \quad (1)$$

Let us adapt this model to the statistical analysis of university network load. Self-similarity of time series formed from the university network load is estimated [8], when a self-similar symmetrical process has infinite variance. We used *α*-stable distribution $S_\alpha(\beta, \delta, \gamma)$ to model the asymmetry and skewness of self-similar network traffic, where α is the stability index, $\beta$ is the skewness index, $\delta$ is the scale index, $\gamma$ is bias index [2]. It should be noted that such a model has a Pareto property.

**Description of the network model**

Let us consider a GI/G/m//N multichannel service system with *m=10* channels, having bounds for the number of packets in a buffer and the waiting time for service [21, 22].

Assume that $N_{SP}$ is a node buffer memory capacity used to preserve packet while be served, $N_n$ is a number of packets in the buffer after departure of *n* packets from the system, and $L$ is the number of lost data packets in the system. The FIFO tail drop and LIFO tail drop are used for buffer serving [9]. All channels are set free at the initial state of the system (*t=0*). The arriving packet to the system is placed in buffer if all channels are full and $N_n < N_{SP}$.

The time series $\tau_0, \tau_1, ...\tau_n$ and $x_0, x_1, ...x_n$ are generated, where $\tau_i$ is the time between adjacent packets appearance in the system, $x_i$ is the packet service time in channel. Packet transmission characteristics are calculated by these time series, taking into account the distribution of series elements and service procedures. Let us explore the node work efficiency, when the offered and served traffics are Markov or self-similar. Formulas are used by simulating the Markov process

$$\tau_i = -\frac{\ln(\xi_i)}{\lambda}, \; x_i = -\frac{\ln(\zeta_i)}{\mu}, \quad (2)$$

where $\xi_i$, $\zeta_i$ are independent random values uniformly distributed in the unit interval. Formulas are used for simulating a self-similar process:

$$\begin{cases} \tau_i = \dfrac{\sqrt[\alpha]{\ln(\xi_i)/\ln(\omega_i)}}{\lambda}, \\ x_i = \dfrac{\sqrt[\beta]{\ln(\zeta_i)/\ln(\upsilon_i)}}{\mu}, \end{cases} \quad (3)$$

where $\xi_i$, $\zeta_i$, $\omega_i$, $\upsilon_i$ are independent random values uniformly distributed in the unit interval. These formulas are derived by using the property of Poisson flow be distributed by Pareto law if the parameter of this flow is distributed with respect to other Poisson distribution.

Using $t_{n+1} = t_n + \tau_{n+1}, t_0 = 0$ we calculate time series of data packets arrival moments. The $(n+1)^{th}$ packet departure time from the system is calculated by using the formula: $s_{n+1} = t_{n+1} + w_{n+1} + x_{n+1}$, where $w_{n+1}$ is the $(n+1)^{th}$ packet waiting time in the buffer. Using the buffer service discipline FIFO tail drop and gSBB, the $w_{n+1}$ is calculated by the formula: $w_{n+1} = \max[0, \min[w_n + x_n - \tau_{n+1}, w_{\lg L}]]$, when $N_n < N_{SP}$, else $w_{n+1} = 0$, and data packet loss if all channels are busy. The number of packets remaining in the buffer, after departure of $(n+1)^{th}$ packet from system, is calculated by the recurrent formula: $N_{n+1} = \min[N_{SP}, N_n + v_{n+1} - 1]$, where $v_{n+1}$ is the number of arriving packets between departure of $n^{th}$ and $(n+1)^{th}$ packet. The number of lost packets $L_{n+1}$ between departure $n^{th}$ and $(n+1)^{th}$ packet is equal to

$L_{n+1} = \max[0, N_n + v_{n+1} - N_{SP} - 1]$ [23].

In [18] it have proved that self-similar traffic is modelled by the formula on the base of gSBB

$$f^{self-similar}(x) = C_\alpha \left( \frac{\rho - m}{\delta} \right)^{-\alpha}, \qquad (4)$$

if the inequality $P\left\{ \hat{A}(t;\rho) > x \right\} \le f^{self-similar}(x)$ sis sattisfied. Here $C_\alpha$ and $m$ are calculated through $S_\alpha(\beta,\delta,\gamma)$ and $x$ parameters.

The Poisson traffic is modelled by the formula on the base of gSBB

$$f^{Poisson}(x) = 1 - (1-\eta) \cdot \sum_{i=0}^{k} \left[ \frac{[\eta(i-k)]^i}{i!} e^{-\eta(i-k)} \right], \qquad (5)$$

if satisfies the inequality $P\left\{ \hat{A}(t;\rho) > x \right\} \le f^{Poisson}(x)$.

Here $\eta = \frac{\lambda \overline{S}}{\rho}$, and $k = \left[ \frac{x}{\overline{S}} \right]$, where $\overline{S}$ – average packet length.

Developed the queuing multichannel network modelling system GI/G/10//N is based on this model. The FIFO tail drop or LIFO tail drop buffer service disciplines are used in network node.

**Research results in the GI/G/m//N network**

The network simulation system MulNodSimSys (Multichannel Node Simulation System) is developed by using the model described above. It is able to simulate network traffic and it serves for many times by changing network node and traffic service parameters. MulNodSimSys presents a statistical estimation by processing the results simulated. The 67760 queues have been simulated with these parameters with the length of each queue $N = 1000000$, the number of data packets that have been served $n \ge 100000$, $0.1 \le \lambda \le 50$, $0.1 \le \mu \le 50$, $1.1 \le \alpha \le 1.9$. Each queue was served for several times by varying $1 \le N_{SP} \le 200$ and the $SP_{disc} \in [FIFO, LIFO]$, where $SP_{disc}$ is the buffer queues serving discipline. Queues are decomposed into 8 groups, by the traffic class (Poisson marked P, self-similar marked S) and buffer service discipline. By analysing the dependence of intensity of offered and served traffics in the network node on traffic and node properties the queues have been simulated by re-electing all $\lambda$, $\mu$, $\alpha$ and $SP_{disc}$ values.

The input parameters of simulation are $N_{SP}$, $\lambda$, $\rho$, $\alpha$. The output variables are: $P_L$ is the probability of packets losses, $P_{serv}$ is the probability that the packet will be served, $\overline{T}_{SP}$ is the average waiting time in the buffer, $\overline{T}_{delay}$ is the average packet delay in the node, $\overline{N}_{applsyst}$ is the average quantity of packets in the system, $T_{SPfull}$ is the full buffer time. For finding out the research results, the regression analysis is used. The estimates are grouped by $SP_{disc}$ values, analysing the offered and served traffic. Fisher statistics is calculated in order to determine the relationship of dependent and independent variables, the $P_F$ probability to estimate that this dependence is not random.

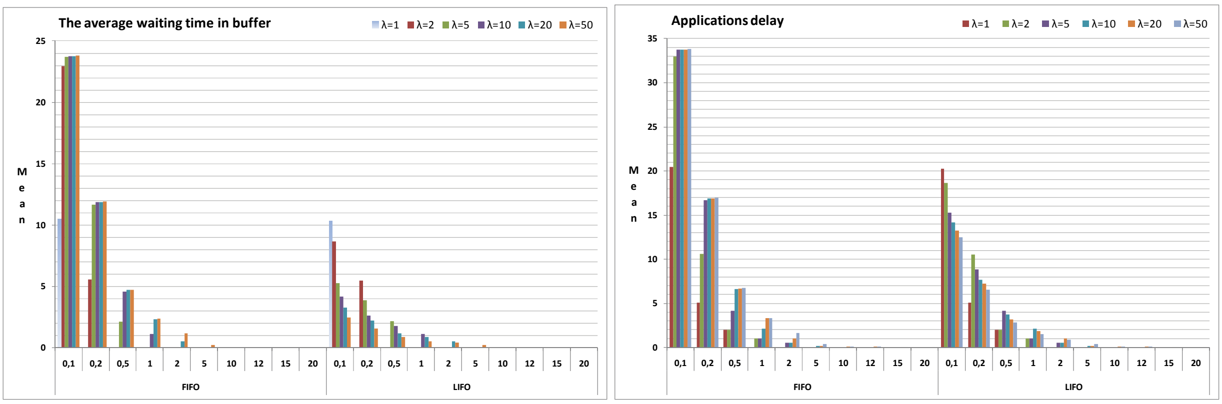
It should be noted that estimation of impact $N_{SP}$ and $SP_{disc}$ on output variables shows, that the $\overline{T}_{delay}$ for PS type of traffic is increased when the buffer service discipline is FIFO. The coefficient of determination $r^2$ shows that a linear dependence established between $N_{SP}$ and $\overline{T}_{SP}, \overline{T}_{delay}, \overline{N}_{applsyst}, T_{SPfull}$ is very strong, between $N_{SP}$ .and $P_L, P_{serv}$ it is average. In all the analysed cases Fisher statistics and $P_F$ we see that the dependence observed between input and output variables in not random.

It is established that the input traffic intensity affects $P_L, \overline{T}_{SP}$ and $\overline{T}_{delay}$, when the traffic is of PP and PS. The $\overline{T}_{SP}$ and $\overline{T}_{delay}$ are greater when $SP_{disc} = FIFO$. The buffer service discipline has no impact on data packet's service parameters in the node if the arrival traffic is self-similar (SP, SS queues). The node with the buffer queue discipline LIFO serves better for high traffic loads.

The network traffic has been analysed, when $\rho > 1$. The research results of estimated $\overline{T}_{SP}$ and $\overline{T}_{delay}$ for PP and PS type traffic are shown in Fig. 1 and Fig 2. The average values and standard deviation are computed for $\overline{T}_{SP}$ and $\overline{T}_{delay}$. It should be noted that the results of analysis show that for $1 < \rho < 10$, $\overline{T}_{SP(LIFO)} \approx \overline{T}_{SP(FIFO)}$ and $\overline{T}_{delay(FIFO)} \approx \overline{T}_{delay(LIFO)}$. For $\rho \ge 10$ $P_{serv(FIFO)} < P_{serv(LIFO)}$, i.e. the data packets are served more than twice faster, when the buffer queue service discipline used is LIFO and $P_{L(FIFO)} > P_{L(LIFO)}$.

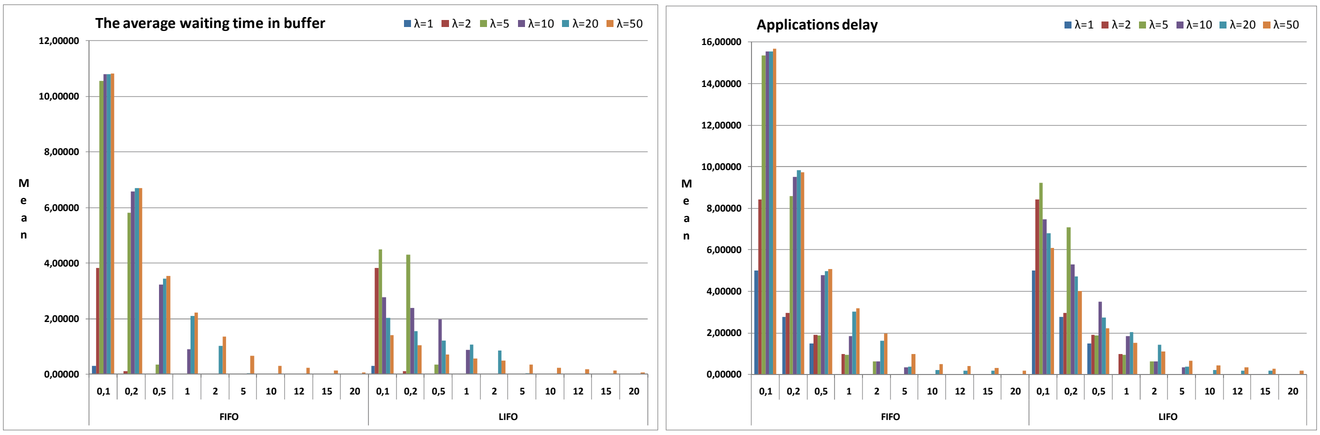
In summary we can state that, if $\lambda$ is larger than ten times $\mu$, for PP type traffic, data packets are served better, when the node buffer queue service discipline is LIFO. In Fig. 1 are shown, that the $\overline{T}_{SP}$ and $\overline{T}_{delay}$ are twice smaller when buffer queue service discipline is LIFO for PP type traffic. Similar results are for PS type traffic. The results are shown in Fig. 2, thus, the $\overline{T}_{SP}$ and $\overline{T}_{delay}$ are smaller twice when buffer queue service discipline is LIFO for PS type traffic. SP and SS type traffic, the FIFO and LIFO buffer queue service discipline doesn't have any impact on $\overline{T}_{SP}$ and $\overline{T}_{delay}$.

When evaluating $\overline{T}_{SP}$ and $\overline{T}_{delay}$ dependence on the traffic type, we have determined that, for SP type traffic, $\overline{T}_{SP}$ is more than 14 time less, $\overline{T}_{delay}$ more than 1.4 times less than in the analogous PS and PP type traffic. For the SS type traffic, $\overline{T}_{SP}$ is more than 3.6 times less, $\overline{T}_{delay}$ more than 3.4 times less than in the analogous PS and PP type traffic.




a) b)

**Fig. 1.** $\overline{T}_{SP}$ (a) and $\overline{T}_{delay}$ (b) estimates with $\rho > 1$ for PP type traffic




a) b)

**Fig. 2.** $\overline{T}_{SP}$ (a) and $\overline{T}_{delay}$ (b) estimates with $\rho > 1$ for PS type traffic

Interdependence between $\alpha$ and $P_L, P_{serv}, \overline{T}_{SP}, \overline{T}_{delay}, \overline{N}_{applsyst}, T_{SPfull}$ is analysed and the link between dependent and independent variables is observed. When increasing self-similarity, the $\overline{N}_{applsyst}$ slowly increases, but the dependence on the buffer queue service discipline is not observed.

The channel load stability is evaluated, as $\rho < 1$, $\rho = 1$, $\rho > 1$ and independent variables are $\lambda$ and $\mu$. The channels are unevenly loaded, as $\rho < 1$ and $\rho = 1$, because the offered traffic is lesser or equal to the node service rate. In these cases, the buffer queue service discipline has no influence on channel work.

It is shown when $\rho > 1$ and the offered traffic always exceeds the network node data packet service rate. The average numbers of transmitted data packets in channels are calculated by increasing the traffic intensity and changing the offered and served traffic properties. From the analysis of variation, we have observed that when increasing the offered traffic, the channel load changes evenly. For the self-similar network traffic with $\lambda > 12$ and for the Poisson network traffic as $\lambda > 5$, the network node channels are unable to serve all the arriving data packets. It can be state that, if the network node service traffic is self-similar, the data packet service conditions are better as compared with that of Poisson, at the same offered traffic intensity.

## Conclusions

We have established a very strong dependence between $N_{SP}$ and $\overline{T}_{SP}, \overline{T}_{delay}, \overline{N}_{applsyst}, T_{SPfull}$, and the average dependence between $N_{SP}$ and $P_L, P_{serv}$, with reference to the regression analysis results and the determination coefficient $r^2$. The calculated Fisher statistics and $P_F$ show that the dependences defined between dependent and independent variables are not random. It also established that $\overline{T}_{delay}$ for PS type traffic was increased when the buffer queue service discipline was FIFO.

Relationships between $\lambda$ and $P_L, P_{serv}, \overline{T}_{SP}, \overline{T}_{delay}, \overline{N}_{applsyst}, T_{SPfull}$ have been established as well. The results of analysis show that the offered traffic intensity mainly influences $P_L, \overline{T}_{SP}$ and $\overline{T}_{delay}$. The buffer queue service is better, if the queue service discipline is LIFO ($\rho \geq 10$) for PP and PS type traffic. For SP and SS type traffic, the buffer queue service discipline does not have any impact on the data packet service parameters.

When all the simulated traffic parameters are the same, it has been defined that, if the offered traffic is self-similar, the $\overline{T}_{SP}$ and $\overline{T}_{delay}$ are lesser as compared with the Poisson traffic. In this case, the buffer queue service discipline has no impact.

It is established that $\alpha$ and $P_L, P_{serv}, \overline{T}_{SP}, \overline{T}_{delay}, \overline{N}_{applsyst}, T_{SPfull}$ are dependent. By analysing the results we have concluded that, by increasing self-similarity, the $\overline{N}_{applsyst}$ slowly increases. The buffer queue discipline doesn't have any impact on $\alpha$ and other variables.

While estimating the data packets transmitted via channels, it has been obtained that with an increasing offered traffic the channel load changes evenly. It can be stated that for just some offered traffic intensity, the productivity of the network node with the self-similar service traffic is more than twice higher as compared with the network node under the Poisson offered traffic.

The research results can be adapted to upgrading network equipment units. The software modules library SSE (Self-Similarity Estimator) has been developed; it was designed for recording and aggregation of network traffic packets as well as for on-line estimation of self-similarity of network traffic [24]. Taking into account the network traffic characteristics and the results discussed in this article, one can choose the most suitable network node equipment which optimally processes the network overload of traffic.

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**L. Kaklauskas, L. Sakalauskas. Study of the Impact of Self-Similarity on the Network Node Traffic // Electronics and Electrical Engineering. – Kaunas: Technologija, 2011. – No. 5(111). – P. 27–32.**

The article analyses a stochastically bounded the GI/G/m//N circuit switched network model with packet losses, with stochastic input network traffic, stochastic served network node, and deterministic and finite network node buffer capacity. Max-plus algebra instrumentality is used for the network processes analysis. FIFO tail drop or LIFO tail drop buffer is used. We have established that the average waiting time in the queue had increased when the queue service discipline was FIFO as compared with LIFO, while the offered traffic was Poisson and the served in the node traffic was self-similar. The network traffic is served faster in the network node with the buffer queue discipline LIFO, while the offered traffic is Poisson and its intensity exceeds the served in the node traffic 10 times. Ill. 2, bibl. 24 (in English; abstracts in English and Lithuanian).

**L. Kaklauskas, L. Sakalauskas. Srauto savastingumo įtakos kompiuterių tinklo mazgo darbui tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 5(111). – P. 27–32.**

Analizuojamas stochastiškai apribotas GI/G/m//N tinklo modelis su paketų nuostoliais, stochastiniu įtekančiuoju tinklo srautu bei determinuota ir baigtine tinklo mazgo buferio talpa. Tinklo procesų analizei panaudotos *max-plius* algebros priemonės. Tinklo mazguose naudota buferinė *FIFO tail drop* ir *LIFO tail drop* atmintis. Nustatyta, kad vidutinė paraiškos laukimo eilėje trukmė yra ilgesnė, kai eilės aptarnavimo disciplina yra FIFO, įtekantysis srautas – Puasono, o mazgo aptarnavimo srautas pasižymi savastingumu. Kai įtekantysis srautas yra Puasono ir jo intensyvumas daugiau nei 10 kartų viršija tinklo mazgo pralaidumą, geriau tinklo srautą aptarnauja tinklo mazgas su LIFO eilės aptarnavimo disciplina. Il. 2, bibl. 24 (anglų kalba; santraukos anglų ir lietuvių k.).