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SPLINE-APPROXIMATION-BASED RESTORATION FOR SELF-SIMILAR TRAFFIC

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Розглядається система масового обслуговування вигляду G/M/1/K з розподілом Вейбула. Для самоподібного трафіку розроблена імітаційна модель за допомогою програмного пакету Simulink в середовищі Matlab. За допомогою сплайн-функцій (лінійних та кубічних сплайнів) отримано відновлення самоподібного трафіку за його значеннями в вузлах інтерполяції.

Отримані результати дозволять передбачити необхідний обсяг буферних пристроїв, тим самим запобігти перенавантаження мережі та перевищення нормативних значень характеристик QoS

Ключові слова: самоподібний трафік, розподіл Вейбула, система масового обслуговування, відновлення, сплайн-функції

Рассматривается система массового обслуживания вида G/M/1/K с распределения с распределением Вейбулла. Для самоподобного трафика разработана имитационная модель с помощью программного пакета Simulink в среде Matlab. С помощью сплайн-функций (линейных и кубических сплайнов) получено восстановление самоподобного трафика по его значениям в узлах интерполяции.

Полученные результаты позволят предусмотреть требуемый объем буферных устройств, тем самым избежать перегрузок в сети и превышений нормативных значений характеристик QoS

Ключевые слова: самоподобный трафик, распределение Вейбулла, система массового обслуживания, восстановление, сплайн-функции

1. Introduction

The development of modern telecommunications is connected with the active implementation of Next Generation Networks (NGN), which are multi-service, multiprotocol and invariant to switching technologies. The concept of NGN implies active implementation of high-speed multiservice access technologies (xDSL, FTTx/PON, BWA), packet switching technologies (Ethernet) and technological development of the transport network (IP/MPLS) controlled by a Softswitch [1].

Traffic in the NGN is bursty and heterogeneous, because it is formed by a variety of different in their characteristics sources including services and network applications. The process of traffic service is associated with the provision of a wide range of services including high-speed voice, data and video transmission (Triple Play Service) [1].

Self-similar traffic has a special structure, which is determined by the burstness and presence of a significant number of pulsations. In practice, this is because packets arrive at the switching node in groups rather than one by one. Buffer devices have limited sizes, which leads to an increase in the packet queues at the switching nodes. Therefore, the delay time and probability of packet loss increase. This often leads to possible overloads of network nodes and buffer devices and, respectively, significantly affects Quality of Service. Thus, special attention must be paid to maintaining QoS characteristics when servicing packet traffic in NGN.

The packet traffic serviced in NGN is characterized by the appearance of self-similar (fractal) properties, implying the existence of a long-term dependence between the arrival instants of the packets, determined by the correlation function at various moments. In addition, self-similar traffic has a structure that persists with multiple scaling, which is called scale invariance. The flow of self-similar traffic is also characterized by the presence of memory, i. e. the number of requests arriving to a queuing system after the moment t depends on the number of requests received before the instant t. Thus, it can be noted that the self-similarity of traffic assumes invariance to the flow behavior under changes of observation time scales and retains a propensity for "flashes" on the time scale. The Hurst parameter H $0.5 \leq H < 1$ is used as a quantitative measure of the degree of self-similarity for traffic [2–4].

The Pareto, Weibull or lognormal distributions are most often used to describe self-similar traffic, taking into account that the arrival times of packets have distributions with "long tails" [2–4].

The interest of researchers to self-similar traffic simulation served as an incentive to search for effective methods of traffic restoration. The known methods of traffic approximation (polynomial, fractional-rational, piecewise-linear, etc.) proved to be rather limited and unacceptable for self-similar traffic [5, 6]. This is due to the fact that self-similar traffic is characterized by the presence of a significant number of "peaks", "bursts" and a long-term dependence between the instants of packets arrivals. Therefore, the use of traditional methods of approximation often leads to significant errors during traffic restorations. At the same time, the use of spline and wavelet approximations has become an alternative to the approximations mentioned above. Spline approximation has the following advantages [5, 6]:

– splines are more resistant to local disturbances;

– spline approximation has good convergence and is fairly simple to implement with the help of software products.

The experience of using spline approximation shows that in all known cases it was possible to achieve tangible results in comparison with traditional methods. In some cases, the use of splines makes it possible to improve the accuracy of the obtained results, in others – significantly reduces the number of calculations, and, thirdly, it allows to solve tasks that otherwise would not be possible to solve. Therefore, the use of spline approximation in restoration of self-similar traffic is a relevant problem, the solution of which will allow accurate and fast approximation of simulated traffic.

2. Literature review and problem statement

Problems related to the study of self-similar traffic often arise along practical implementation of the NGN concept. The process of solving these problems is connected to self-similar traffic simulations and allows determining the dependence between the volume of serviced traffic with guaranteed QoS characteristics and network parameters ensuring efficient utilization of available network resources.

It is important to obtain the necessary traffic characteristics, when simulating self-similar traffic. Authors of the works [7–9] propose to apply an envelope curve to the values of self-similar traffic, while the approximation determines the use of a definite distribution law. In this case, if the self-similar traffic has "pulsations" and "bursts" at different instants of time, then the error of such estimations can be quite significant. The values obtained with the help of the distribution law allow us to find certain probabilistic characteristics of the self-similar traffic approximation. On the contrary, the use of traffic restoration will allow obtaining a quantitative estimation of the received (requests for service, packets) simulation results at certain instants of time, set with a certain step. Thus, it allows obtaining values of QoS characteristics, and providing the necessary structure of the hardware-software facilities of network nodes even at the design stage of NGN. After all, the way of simply building up the amount of hardware and software capabilities, in the process of NGN operation, is ineffective because available resources are quickly depleted due to the constant development of new services and applications.

Most often, researchers use the Simulink package of Matlab [8, 9] as a simulation environment. But the work [8] states that during simulations in Simulink of the Matlab environment, traffic packets are generated only for one set distribution, in this case – the Pareto distribution. The work [9] suggests using the SimEvents package, which allows generating packets for different distributions, but such an approach makes simulation quite complicated due to a large number of additional parameters. At the stage of self-similar traffic model selection, it is necessary to consider that traffic characteristics are quite dynamic and depend on a significant number of parameters and network settings. Considering each traffic stream to be self-similar, then, according to [10], the multiplexed stream also has the property of self-similarity. The simulation capabilities are often limited to the choice of the traffic model, as in [11], or they are aimed at some specific kind of traffic and are far from universal. At the same time, for an adequate description of traffic during simulation, taking into account all the factors mentioned above, the traffic model itself becomes more complicated [12], for example, due to the additional parameter of productivity. Sometimes such complication arises due to additional parameters, as in the work [13].

Simulation of traffic, as a rule, is accompanied by its restoration with the subsequent approximation. According to [14], various types of approximations are proposed to approximate self-similar traffic, with the assumption of a Gaussian traffic generation process, but the work neither compares these methods nor gives recommendations on their use. In this case, the question arises of selecting the approximation method for the restoration of self-similar traffic.

3. The aim and objectives of the study

The aim of this work is to restore self-similar traffic with the help of spline functions (linear and cubic splines) approximations in order to improve QoS characteristics. This will allow using the obtained results at the stage of NGN design to select the buffer devices of the necessary capacity and to avoid congestions in the network and excessive values of QoS characteristics.

To achieve this aim, it is necessary to complete the following tasks:

– to develop a simulation model for the Simulink software package of the Matlab environment and perform simulation of self-similar traffic for a QS of the G/M/1/K type;

– to use linear and cubic splines in the process of self-similar traffic restoration;

– to develop recommendations on application of the spline approximation apparatus for improving QoS characteristics.

4. Simulation of self-similar traffic in the Simulink package of the Matlab environment

The self-similar flow described by a fractal Brownian motion was used for simulations of self-similar traffic with the Simulink package of the Matlab environment. Let us simulate self-similar traffic for a queuing system (QS) of the G/M/1/K type [2].

In this case, to simulate the process of requests arrivals, the intervals between arrivals are described by an arbitrary distribution of G, and we use the Weibull distribution with the service time distributed according to the exponential law.

Then, the considered QS will be of the W/M/1/K type.

Let us consider the Weibull distribution given by the following differential distribution function [2]:

$$f(x)=\begin{cases}\alpha\beta x^{\alpha-1}e^{-\beta x^{\alpha}}, & x\geq 0,\\ 0, & x\leq 0,\end{cases} \tag{1}$$

where α – distribution curve shape parameter, ($0<\alpha<1$); $\alpha=2-2H$, H – Hurst parameter, $(0{,}5\leq H\leq 1)$; $\beta=\left[\lambda\Gamma\left(1+\frac{1}{\alpha}\right)\right]^{-1}$ – distribution parameter; $\beta>0$, Γ – gamma function; λ – intensity of arrivals to QS.

The integral distribution function of Weibull takes the form of [2]:

$$F(x)=1-e^{-\beta x^{\alpha}}. \tag{2}$$

To generate a sample of random variables with the Weibull distribution, let us find the inverse function of the integral distribution function (2). Solving the equation (2) with respect to the unknown x, we obtain:

$$e^{-\beta x^{\alpha}}=1-y,$$

$$-\beta x^{\alpha}=\ln(1-y),$$

$$x^{\alpha}=-\frac{1}{\beta}\ln(1-y),$$

$$x=\left[-\frac{1}{\beta}\ln(1-y)\right]^{\frac{1}{\alpha}}. \tag{3}$$

Thus, the inverse function, which is determined finitely only on the interval (0; 1), will have the form of:

$$F^{-1}(y)=\left[-\frac{1}{\beta}\ln(1-y)\right]^{\frac{1}{\alpha}}. \tag{4}$$

Having a sequence of uniformly distributed random numbers, for example, generated in Simulink, we can calculate the values of random numbers with the Weibull distribution and the mean value:

$$\mu=\beta^{-\frac{1}{\lambda}}\Gamma(1+\frac{1}{\lambda}),$$

with the help of the following algorithm:

$$X_i=\left[-\frac{1}{\beta}\ln(1-U_i)\right]^{\frac{1}{\alpha}}, \tag{5}$$

where U_i denotes a random value uniformly distributed within the interval (0; 1).

Let us note that in the same way, it is possible to generate random intervals with any given distribution law.

The mathematical expectation for the Weibull distribution has the form [2]:

$$\mu=\beta^{-\frac{1}{\alpha}}\Gamma\left(1+\frac{1}{\alpha}\right). \tag{6}$$

The dispersion of the Weibull distribution [2]:

$$\sigma^2=\beta^{-\frac{2}{\alpha}}\left[\left(\Gamma\left(1+\frac{2}{\alpha}\right)-\Gamma^2\left(1+\frac{1}{\alpha}\right)\right)\right], \tag{7}$$

where $\Gamma(x)$ – Euler gamma function.

Let us use the following characteristics as an initial data for the W/M/1/K QS: λ – intensity of arrivals to QS, λ=250 packets/s; μ – duration of service, μ=125 s; K – queue length, K=1000 requests.

We set the value of the Hurst parameter of H=0.6 to simulate the self-similar traffic. Then, for the Weibull distribution, the parameters α and β are, respectively, $\alpha\approx0.8$ and $\beta\approx0.00405$.

Simulations were performed using the Simulink package of the Matlab environment with the following initial data: N – the number of requests; T – time of requests arrivals.

It is possible to conclude the following, according to the simulation results shown in Fig. 1. The graph shows that the process is uneven and corresponds to the self-similarity criteria described above. There is a large-scale invariance, the presence of "bursts" and the long-term dependence between the time instants of requests arrivals.

Let us consider the values of self-similar traffic on the [a, b] interval. We have divided this interval as follows:

$$a=x_0<x_1<x_2<\ldots<x_n=b,$$

where $x_{i+1}=x_i+h$, $h=\frac{b-a}{n}$ – partition step; n – the number of partition subintervals.

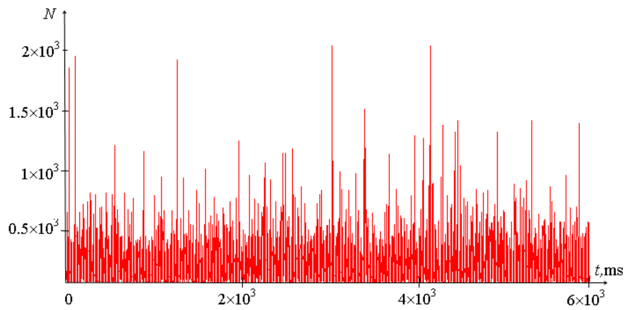

Fig. 1. Simulation of self-similar traffic for the W/M/1/K QS within the range of [1;6000] ms

In our case, we set a=0, b=800, h=20. Then n=40, that is, 40 partition subintervals $[x_i; x_{i+1}]$, and $i=\overline{0,39}$, which is shown in Table 1.

Table 1

Partition subintervals

$[x_0, x_1]$	[0; 20]	$[x_5, x_6]$	[100; 120]	$[x_{10}, x_{11}]$	[200; 220]
$[x_1, x_2]$	[20; 40]	$[x_6, x_7]$	[120; 140]	...	...
$[x_2, x_3]$	[40; 60]	$[x_7, x_8]$	[140; 160]	$[x_{37}, x_{38}]$	[740; 760]
$[x_3, x_4]$	[60; 80]	$[x_8, x_9]$	[160; 180]	$[x_{38}, x_{39}]$	[760; 780]
$[x_4, x_5]$	[80; 100]	$[x_9, x_{10}]$	[180; 200]	$[x_{39}, x_{40}]$	[780; 800]

The obtained distribution of the sample is represented as a histogram in Fig. 2.

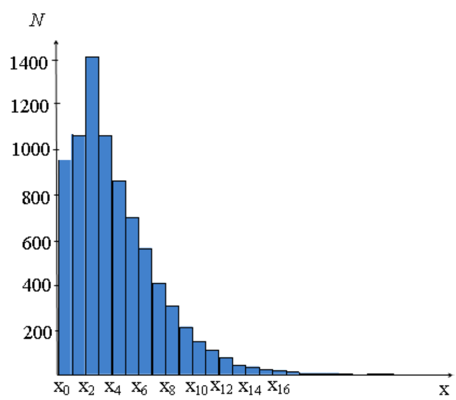

Fig. 2. The histogram of self-similar traffic

It should be noted that increasing the number of partitions within an interval, when constructing a histogram of self-similar traffic, reduces a length of a particular subinterval until it reaches zero. Replacing the stepped line of the obtained histogram with the continuous curve, we obtain a graph of the density function for the random variable [2].

Let us use the sample data to construct an empirical distribution function for requests arrivals to the QS of the W/M/1/K type within the interval of [1; 6000]. By the form of this curve, we assume that the distribution occurs according to the Weibull distribution law.

The received estimates of requests arrivals, namely, mathematical expectation m_x, variance D_x and standard deviation σ_x are shown in Table 2.

After the assumption is made about the theoretical law of traffic distribution, the question arises of how accurately it matches the statistical distribution obtained on the basis of traffic simulations. Using the Pearson criterion χ^2 [2], it is not difficult to verify the consistency between theoretical and statistical distributions.

Table 2

Mathematical expectation m_x, variance D_x and standard deviation σ_x of arrivals to the W/M/1/K QS

Mathematical expectation, m_x	Variance D_x	Standard deviation σ_x
68.66	3951.54	62.86

5. Restoration of self-similar traffic using spline-function approximations

Let us consider self-similar traffic simulations for the W/M/1/K QS using the Simulink package of the Matlab environment. To restore self-similar traffic, we will use spline approximations (linear and cubic) [16–18], with the help of which it is possible to solve the problems of processing statistical data and finding experimental dependences with a rather complex structure [5, 6].

Let us perform the restoration of the self-similar traffic shown in Fig. 1 through approximation with the linear spline $S_1(t)$. Let's consider a fragment of self-similar traffic (Fig. 3) for the W/M/1/K QS that experiences arrivals within the time interval of [2150; 2169] ms.

Suppose that in the interval of [0; T] the results of traffic simulation are known. We divide the [0; T] interval with points Δ: $0=t_0<t_1<...<t_n=T$ into intervals $[t_i; t_{i+1}]$, $i=\overline{0,n-1}$. At each interval, we construct a polynomial of a certain degree. We use a linear spline as such a polynomial [15].

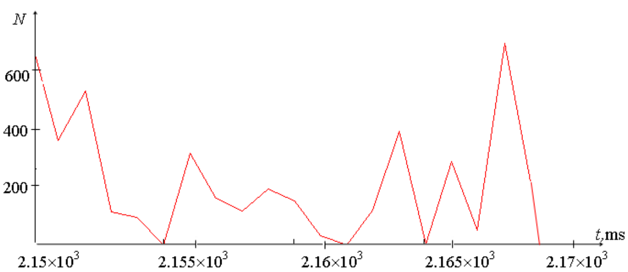

Fig. 3. A fragment of self-similar traffic for the W/M/1/K QS

According to [15], the interpolating linear spline $S_1(t_1)$ on the interval of $[t_i; t_{i+1}]$, $i=\overline{0,n-1}$ is represented as the continuous piecewise-linear function. Let us assume that the values of $s_i=s(t_i)$, $i=\overline{0,n}$ of the function s(t) are set in the Δ grid nodes and the function is defined within the interval of $[t_i; t_{i+1}]$, $i=\overline{0,n-1}$.

The interpolation spline $S_1(t_i)$ is determined by the following conditions [15]:

$$S_1(t_i)=S_i,\ i=\overline{0,n}. \tag{6}$$

If we denote $h_i=t_{i+1}-t_i$, then for $t\in[t_i; t_{i+1}]$, $i=\overline{0,n-1}$ the equation of the linear spline will have the form [12]:

$$S_1(t)=f_i\frac{t_{i+1}-t}{h_i}+f_{i+1}\frac{t-t_1}{h_i}, \tag{7}$$

where $f_i=S(t_i)$, $i=\overline{0,n}$ or

$$S_1(t)=f_i+\frac{t-t_1}{h_i}(f_{i+1}-f_i). \tag{8}$$

Let us consider self-similar traffic within the selected interval of [2150; 2169] ms, with the specified uniform partitions grid having the step of h=0.05. The number of requests in each interpolation node is known for each split point. We restore traffic within the interval of [2150; 2169] ms, using the linear interpolation spline $S_1(t_i)$ (6)–(8) at the given interpolation nodes t_i, $i=\overline{0,n}$ (Fig. 4).

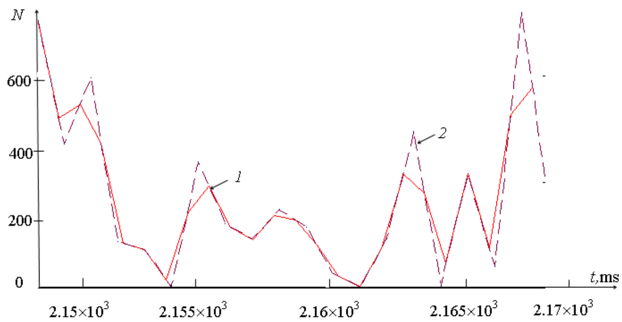

Fig. 4. Approximation of a fragment of self-similar traffic using the linear spline: 1 – simulated self-similar traffic; 2 – traffic restoration with linear spline approximation

Let us consider the approximation of self-similar traffic by a cubic spline $S_3(t)$ within the interval of [2150; 2169] ms (Fig. 5).

Suppose that in the interval of [0; T] the results of traffic simulation are known. We divide the [0; T] interval with points Δ: $0=t_0<t_1<\ldots<t_n=T$ into intervals $[t_i; t_{i+1}]$, $i=\overline{0,n-1}$. At each interval we construct a polynomial of a certain extent [15].

We use a cubic spline as such a polynomial. Thus, we obtain a piecewise-continuous function that determines a cubic spline within the interval [0; T]. Let the values of some function $s_i=s(t_i)$ $i=\overline{0,n}$ be set on the interval [0; T] at the grid nodes Δ: $0=t_0<t_1<\ldots<t_n=T$.

According to [15], the interpolating cubic spline $S_3(t_i)$ satisfies the following conditions:

$$S_3(t_i)=S_i,\ i=\overline{0,n-1}, \tag{9}$$

– it is a polynomial of the third degree within each of the $[t_i; t_{i+1}]$, $i=\overline{0,n-1}$ intervals,

– within the whole [0; T] interval there is the continuity of second derivatives

$$S''_3(t_i)=M_i,\ S''_3(t_{i+1})=M_{i+1},\ S''_3(t_0)=M_0,\ S''_3(t_1)=M_1.$$

Then, for the $S_3(t)$:

$$S_3(t)=f_i(1-t)+f_{i+1}t-\frac{h_i^2}{6}t(1-t)\left[(2-t)M_i+(1+t)M_{i+1}\right],$$

$$t\in[t_i; t_{i+1}],\ i=\overline{0,n-1}, \tag{10}$$

where $f_i=S(t_i)$, $i=\overline{0,n}$.

Let us specify a uniform grid of partition in order to examine self-similar traffic within the interval of [2150; 2169] ms. The number of requests in each interpolation node is known for every split point.

Let us use the cubic spline and expressions (9), (10) in order to obtain traffic restoration at the given interpolation nodes t_i, $i=\overline{0,n}$ (Fig. 5).

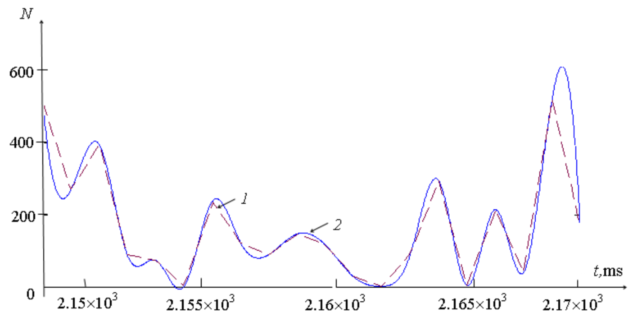

Fig. 5. Approximation of a fragment of self-similar traffic using the cubic spline: 1 – simulated self-similar traffic; 2 – traffic restoration with cubic spline approximation

6. Discussion of the results of self-similar traffic restoration

In this work, we have performed traffic restorations using linear and cubic splines. From Fig. 4, 5, we can conclude that the cubic spline approximation for self-similar traffic, which is typical for high-speed data transmission services, will be better for traffic recovery than linear spline approximation. However, there is such a kind of self-similar traffic, formed by the services of high-speed data and video transmissions, characterized by the presence of "bursts" and "pulsations;", as well as long-term dependence between instants of requests arrivals. For it, the use of cubic interpolation splines is suggested. To restore voice traffic, which is characterized by smooth changes, the use of linear and cubic interpolation splines is suggested. Thus, to restore traffic in each particular case, it is necessary to use different types of spline-approximation. In the future, it would be interesting to continue the research of restoring self-similar traffic with increased steepness and the presence of "bursts" and "pulsations" with the help of wavelet approximation, in order to perform a comparative analysis of the corresponding results obtained through spline-approximations.

7. Conclusions

1. The simulation model has been developed to examine the characteristics of self-similar traffic within the Simulink software package of the Matlab environment. Simulations of self-similar traffic for the W/M/1/QS have been done. The initial data for the simulation was: the value of the Hurst parameter H=0.65 and the shape parameter of the distribution curve $\alpha\approx0.7$ while the distribution parameter $\beta\approx0.0099$.

2. The restoration of self-similar traffic has been obtained by means of linear and cubic spline approximations.

3. The obtained results make it possible to form recommendations on how to select the necessary hardware and software facilities for network nodes in order to prevent overloads and excessive QoS values for real traffic. To restore self-similar traffic that is characterized by the presence of "bursts" and "pulsations", this study suggests using cubic spline approximations. The linear and cubic splines approximations are suggested to restore self-similar traffic with smooth changes. It would be advisable to use another mathematical apparatus – the wavelet function for self-similar traffic that has increased steepness, "bursts", and "pulsations".

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