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SPLINE-EXTRAPOLATION METHOD FOR RESTORING SELF-SIMILAR TRAFFIC

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МЕТОД СПЛАЙН-ЕКСТРАПОЛЯЦІЇ ПРИ ВІДНОВЛЕННІ САМОПОДІБНОГО ТРАФІКУ

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Анотація. *Розглянуто задачу прогнозування самоподібного трафіку, який володіє значною кількістю сплесків і пульсацій та властивістю довгострокової залежності, за допомогою методу сплайн-екстраполяції з використанням кубічних B-сплайнів. Застосування методу сплайн-екстраполяції дозволило спрогнозувати самоподібний трафік поза аналізованого сегменту часу, на якому розглядається передача пакетних даних в мережі мобільного зв'язку. Запропоновано метод оцінки похибки прогнозування трафіку з використанням методу сплайн-екстраполяції на базі кубічних B-сплайнів. За результатами дослідження встановлено, що кубічні B-сплайни характеризуються високою конструктивністю та простотою практичної реалізації. Їх використання дозволяє значно спростити обчислювальні процеси, використовуючи формалізовані математичні конструкції. На прикладі змодельованого самоподібного трафіку, отриманого в пакеті Simulink середовища Matlab, виконана сплайн-екстраполяція з використанням кубічних B-сплайнів. Це дозволило отримати «трасу» трафіку поза межами розглянутого сегменту, яка відповідає результатам моделювання з визначеною точністю прогнозу. Використання запропонованого методу сплайн-екстраполяції на базі кубічних B-сплайнів має ряд переваг в порівнянні з іншими відомими методами, а саме, простота практичної реалізації, висока точність прогнозу, можливості достатньо точно екстраполювати пікові «сплески» трафіку, що особливо важливо при вирішенні задач в реальному масштабі часу. Практична значимість отриманих результатів дослідження визначається тим, що отримані значення інтенсивності трафіку при відомій завантаженості мережевих вузлів, дозволять оператору на етапі проектування і подальшої експлуатації мережі мобільного зв'язку передбачити необхідний обсяг буферних пристроїв апаратно-програмних засобів мережі, тим самим уникнувши перевантажень в мережі і перевищень нормативних значень характеристик якості обслуговування трафіку. Запропоновано перспективу подальших досліджень за рахунок використання вейвлет-екстраполяції з метою підвищення оцінок точності прогнозування.*

Ключові слова*: самоподібний трафік; прогнозування; екстраполяція; сплайн-функції; кубічний B-сплайн, похибка екстраполяції.*

Abstract. *The problem of predicting self-similar traffic, which has a considerable number of bursts and ripples and the property of long-term dependence, using the method of spline-extrapolation using cubic B-splines was considered in this paper. The application of the spline-extrapolation method allowed to predict self-similar traffic outside the analyzed time segment, which deals with packet data transmission on the mobile network. A method for estimating the traffic predicting error using the method of spline-extrapolation based on cubic B-splines is proposed. According to the results of the study, it is found that cubic B-splines are characterized by high design and ease of practical implementation. Their use makes it possible to greatly simplify computational processes using formalized mathematical constructs. On the example of simulated self-similar traffic received in the Simulink package of the Matlab environment, a spline-extrapolation was performed using cubic B-splines. This made it possible to obtain a "route" of traffic beyond the considered segment, which corresponds to the results of modeling with a certain prediction accuracy. The use of the proposed method of spline-extrapolation based on cubic B-splines has several advantages over other known methods, namely, ease of practical implementation, high accuracy of forecasting, the ability to accurately* *extrapolate peak "bursts" of traffic, which is especially important when solving problems in real time. The practical significance of the results of the study is determined by the fact that the obtained values of traffic intensity with a known load of network nodes, will allow the operator at the stage of design and subsequent operation of the mobile network to predict the required volume of buffer devices network hardware, thereby avoiding network congestion and accidence of regulatory values of traffic service quality characteristics. The prospect of further research is suggested by using wavelet extrapolation to improve the accuracy of estimates predicting.*

***Keywords**: self-similar traffic; predicting; extrapolation; spline-functions; cubic B-spline; extrapolation error.*

INTRODUCTION

Today, mobile communication networks are developing in the direction of fifth-generation 5G/NR (New Radio) networks, the introduction of which will allow the mobile operator to provide high-speed services, including video services, tactile Internet services, 3D-games in real-time, holographic image transmission, e-health and e-education services, industrial and transport automation with support for low packet delay times. The 5G/NR network architecture is based on software-defined radio access networks of the SDR (Software Defined Radio) network and the SDN (Software Defined Networking) core network, and also uses the procedures of network functions virtualization [1-3].

The introduction of a new type of services and interactive applications requires the mobile operator, first of all, to increase the speed of data transmission and ensure the required values of the QoE (Quality of Equipment) characteristics. The maintenance of quality characteristics in mobile communication networks implies the acquisition of traffic characteristics that are served on the network based on its real “routes”.

Studies of real traffic of packet networks conducted by many scientists, for example [4-5], show that traffic in such networks is described by a self-similar random process, and its self-similar nature is manifested by a long-term relationship between traffic values at different time periods. At the same time, there are bursts of intensity that look statistically similar at different time scales [4-5]. In practice, the occurrence of long-term ripples of traffic intensity at arbitrary points in time often leads to a sharp increase in packet delay time, which causes overloading of mobile network nodes and buffer devices and, respectively, has a significant impact on the quality of service of the traffic. Therefore, the solution of the problem of modeling and predicting the characteristics of self-similar traffic is quite an important and relevant task. Properly selected method of forecasting allows to obtain predictions about the availability of the necessary bandwidth to provide the required delay times and provide for possible peak loads in the network. The prediction results will help the operator perform traffic management, thereby ensuring the required QoS characteristics.

Some issues of predicting the characteristics of self-similar traffic are considered by the authors in [6-11]. However, the proposed predicting methods are not universal. There is no single method for predicting the characteristics of self-similar traffic that would allow real-time prediction of the behavior of self-similar traffic, giving the mobile operator the opportunity to take timely measures to prevent network node overloads and the corresponding effects of these changes on QoS service quality.

Therefore, it can be argued about the significant interest of many scientists to the issue under consideration. Earlier, the authors proposed a solution to the problem of predicting self-similar traffic using the spline extrapolation method, that is, recovering self-similar traffic outside the considered time interval using linear and cubic spline functions [12].

The goal of this paper is to predict self-similar traffic using the spline extrapolation method using cubic B-splines and obtaining the required characteristics of QoE. This will allow the development of practical recommendations for the mobile operator to prevent overloading of network nodes and the impact on the quality of service QoE.

SPLINE-EXTRAPOLATION METHOD WITH THE USE OF CUBIC B-SPLINES

To predict self-similar prediction of self-similar traffic using cubic in-spline traffic, we use the extrapolation method proposed by the authors in work [12]. Previously, the authors used a spline-extrapolation method based on linear and cubic splines to solve the problem of predicting self-similar traffic. In this paper, as an approximating device, we consider cubic B-splines.

Solution of the extrapolation problem of cubic splines or piecewise polynomials of their representation in many cases is a convenient tool both for solving theoretical problems, as well as computationally. However, in a number of applications, it is more efficient to represent cubic splines through B-splines.

Consider solving the problem of predicting self-similar traffic using cubic B-splines.

Let's look at the self-similar traffic on the segment [*a;b*], which is described by a function $y = f(x)$. Let a partition Δ: $a = x_0 < x_1 < \ldots < x_N = b$ be defined on the interval [*a;b*], where *N* is a positive integer. Let us complement the Δ: $a = x_0 < x_1 < \ldots < x_N = b$ with nodes $x_{-3} < x_{-2} < x_{-1} < a$, $b < x_{N+1} < x_{N+2} < x_{N+3}$. These nodes are chosen arbitrarily. If a periodic case is considered, then the condition must be satisfied $h_{N+i} = h_i$, $i = 0;1;...;N$.

Construct a cubic B-spline, different from zero in the interval (x_{i-2}, x_{i+2}). B-splines of odd degrees are conveniently numbered by the middle node of their carrier intervals. The desired B-spline will be denoted by $B_i(x)$. Set $y_p = B_i(x_p)$, $M_p = B_i''(x_p)$. For $B_i(x)$, the following equations are [13]:

$$\mu_p M_{p-1} + 2M_p + \lambda_p M_{p+1} = \frac{6}{h_{p-1}+h_p}\left(\frac{y_{p+1}-y_p}{h_p} - \frac{y_p - y_{p-1}}{h_{p-1}}\right), \tag{1}$$

where $p = i-1; i; i+1$, $\mu_i = \frac{h_{i-1}}{h_{i-1}+h_i}$, $\lambda_i = 1-\mu_i$ $\lambda_i = 1-\mu_i$.

As $B_i(x) = 0$, for $x \notin [x_{i-2}; x_{i+2}]$, then

$$B_i^{(r)}(x_{i-2}) = B_i^{(r)}(x_{i+2}) = 0,\ r = 0;\ 1;\ 2. \tag{2}$$

Whereas, for the B-spline, the relation [14-15]

$$B_i(x) = y_i(1-t) + y_{i+1}t - \frac{h_i^2}{6}t(1-t)\left[(2-t)M_i + (1+t)M_{i+1}\right], \tag{3}$$

where $x \in [x_i; x_{i+1}]$, $t = \frac{x - x_i}{h_i}$, $h_i = x_{i+1} - x_i$, we get

$$B_i'(x) = \frac{y_{i+1}-y_i}{h_i} - \frac{h_i}{6}\left[(2-6t+3t^2)M_i + (1-3t^2)M_{i+1}\right], \tag{4}$$

$$B_i''(x) = M_i(1-t) + M_{i+1}t. \tag{5}$$

Then conditions (2), due to equalities (3-5) can be represented by equalities:

$$\begin{cases} y_{i-2} = y_{i+2} = 0; \\ M_{i-2} = M_{i+2} = 0; \\ y_{i-1} = \dfrac{1}{6} h_{i-2}^{2} M_{i-1}; \\ y_{i+1} = \dfrac{1}{6} h_{i+1}^{2} M_{i+1}. \end{cases} \tag{6}$$

Found parameters (6) are excluded from (1), which will lead to the system of equations:

$$\begin{cases} (h_{i-2} + h_{i-1})(h_{i-2} + 2h_{i-1}) M_{i-1} + h_{i-1}^{2} M_{i} = 6 y_{i}; \\ (h_{i-2} + h_{i-1}) M_{i-1} + (h_{i-1} + h_{i}) M_{i} + (h_{i} + h_{i+1}) M_{i+1} = 0; \\ h_{i}^{2} M_{i} + (h_{i} + h_{i+1})(2h_{i} + h_{i+1}) M_{i+1} = 6 y_{i}. \end{cases} \tag{7}$$

The result was a system of three equations for finding four parameters: $y_i, M_{i-1}, M_i, M_{i+1}$. One parameter can be used at your own discretion. Assuming, for example,

$$y_{i} = \frac{h_{i-1}(h_{i-2} + h_{i-1})(2h_{i} + h_{i+1}) + h_{i}(h_{i} + h_{i+1})(h_{i-2} + 2h_{i-1})}{(h_{i-1} + h_{i})(h_{i-2} + h_{i-1} + h_{i})(h_{i-1} + h_{i} + h_{i+1})}. \tag{8}$$

From the system of equations (7), we find:

$$\begin{cases} M_{i-1} = \dfrac{6}{(h_{i-2} + h_{i-1})(h_{i-2} + h_{i-1} + h_{i})}; \\ M_{i} = \dfrac{6\left[(h_{i-2} + h_{i-1} + h_{i})^{-1} + (h_{i-1} + h_{i} + h_{i+1})^{-1}\right]}{h_{i-1} + h_{i}}; \\ M_{i+1} = \dfrac{6}{(h_{i} + h_{i+1})(h_{i-1} + h_{i} + h_{i+1})}. \end{cases} \tag{9}$$

Formulas (6), (8), (9) completely determine the spline $B_i(x)$ on the interval $[x_{i-2}; x_{i+2}]$:

The interpolation cubic spline $S(x)$ can be found using its B-spline representation:

$$S(x) = \sum_{i=-1}^{N+1} b_{i} B_{i}(x).$$

According to [13], it is easy to find the error of extrapolation of self-similar traffic. The quality of the interpolation function is characterized, as $R(x) = S(x) - f(x)$ and it depends on what differential properties the interpolated function $f(x)$ has.

Consider a spline satisfying the conditions

$$S(f; x_{i}) = f_{i},$$

where $i = 0;\ 1;\ldots;\ N$

with boundary conditions of the form

$$S'(f; a) = f'(a); \quad S'(f; b) = f'(b).$$

According to [13], to determine the coefficients b_i, we obtain the system of equations

$$\begin{cases} b_{-1}B'_{-1}(x_0)+b_0B'_0(x_0)+b_1B'_1(x_0)=f'_0; \\ b_{i-1}B_{i-1}(x_1)+b_1B_1(x_1)+b_{i+1}B_{i+1}(x_1)=f_i; \\ b_{N-1}B'_{N-1}(x_N)+b_NB'_N(x_N)+b_{N+1}B'_{N+1}(x_N)=f'_N. \end{cases} \tag{10}$$

where $i=0;\ 1;...;\ N$.

Consider the periodic case. Then the equations of the system of equations (10), describing the problem of extrapolation, have the form:

$$b_{i-1}B_{i-1}(x_i)+b_iB_i(x_i)+b_{i+1}B_{i+1}(x_i)=f_i,.$$

where $i=0;\ 1;...;\ N$.

In matrix form can be written as

$$Ab=f, \tag{11}$$

where $b=(b_1;...;b_N)^T$, $f=(f_1;...;f_N)^T$, T is denotes transposition.

We calculate the error of extrapolation of self-similar traffic using (11)

$$A(b-f)=f-Af. \tag{12}$$

Consider the space C[a;b] of continuous on [a;b] functions with norm

$$\|f(x)\|_{C[a,b]}=\max_{x\in[a,b]}|f(x)|.$$

On the grid Δ: $a = x_0 < x_1 < \ldots < x_N = b$ these functions will be characterized by their oscillation on segments $[x_i;x_{i+1}]$

$$\omega_i(f)=\max_{x',x''\in[x_i,x_{i+1}]}|f(x'')-f(x')|,$$

and the value

$$\omega(f)=\max_{0\le i\le N-1}\omega_i(f).$$

It is known that the characteristic of the function, independent of the grid Δ there is the modulus of $\omega(f;h)$, which is defined as follows

$$\omega_i(f;h)=\max_{\substack{x',x''\in[a,b] \\ |x''-x'|\le h}}|f(x'')-f(x')|,\ h\le b-a.$$

If denoted $\bar{h}=\max_i h_i$ then the following inequalities are:

$$\omega_i(f)\le\omega(f)\le\omega(f;\bar{h}).$$

Then

$$\|f-Af\|=\max_i|f_i-f_{i-1}B_{i-1}(x_i)-f_iB_i(x_i)-f_{i+1}B_{i+1}(x_i)|\le$$
$$\le\max_i\left\{B_{i-1}(x_i)|f_i-f_{i-1}|+B_{i+1}(x_i)|f_i-f_{i+1}|\right\}\le\omega(f).$$

Using the property of normalized B-splines

$$\sum_i B_i(x)=1$$

and expression (12), we find

$$\|b-f\|\le\|A^{-1}\|_{\omega(f)} \tag{13}$$

Further

$$\|S(x)-f(x)\|=\left|\sum_{i=-1}^{N+1}\left[b_i-f(x)\right]B_i(x)\right|\le\left|\sum_{i=-1}^{N+1}\left[b_i-f_i\right]B_i(x)\right|+\left|\sum_{i=-1}^{N+1}\left[f_i-f(x)\right]B_i(x)\right|.$$

Considering (13), we get

$$\left|\sum_{i=-1}^{N+1}\left[b_i-f_i\right]B_i(x)\right|\le\|b-f\|\le\|A^{-1}\|_{\omega(f)}.$$

In addition, for any $x\in[x_i;x_{i+1}]$, where $i=0;1;...;N$,

$$\left|\sum_{i=-1}^{N+1}\left[f_i-f(x)\right]B_i(x)\right|\le\sum_{p=i-1}^{i+2}\left|f_p-f(x)\right|B_p(x)\le 2\omega(f).$$

Finally, we have

$$\left|S(x)-f(x)\right|\le\left(2+\|A^{-1}\|\right)_{\omega(f)} \tag{14}$$

We introduce $\rho=\max_{\mathrm{i}} h_i \big/ \min_i h_i$. According to [13], the matrix A will be ill-conditioned if $\rho\ge(3+\sqrt{5})/2$, then it is advisable to use a grid with a partition step for which $\rho<(3+\sqrt{5})/2$.

SOLVING THE PROBLEM OF EXTRAPOLATION OF SELF-LIKE TRAFFIC BY THE SPLINE-EXTRAPOLATION METHOD ON THE BASIS OF CUBIC B-SPLINES

Consider spline extrapolation using cubic B-splines using the example. To do this, we simulate the self-similar traffic in the Simulink package of Matlab [16–17] environment for the queuing system (QS) W_B/M/1/K with the parameters:

– intensity of packets for service in the QS λ = 125 pack/s,

– packet service time пакетов μ = 150 packs/s,

– the queue length of packets is K = 200 packets,

– the Hurst parameter is H = 0,65,

– the Weibull distribution parameters are α≈0,7 and β≈3,46.

The results of simulating self-similar traffic for given initial data on the [3000; 4000] ms segment are shown in Fig. 1, where *n* is the number of packets and *t* – is the packet arrival time [16–17].

Figure 1 shows that for the obtained self-similar traffic on the [3000; 4000] ms segment, there is a large-scale invariance, the presence of “bursts” of requests and a long-term relation between the moments of their admission.

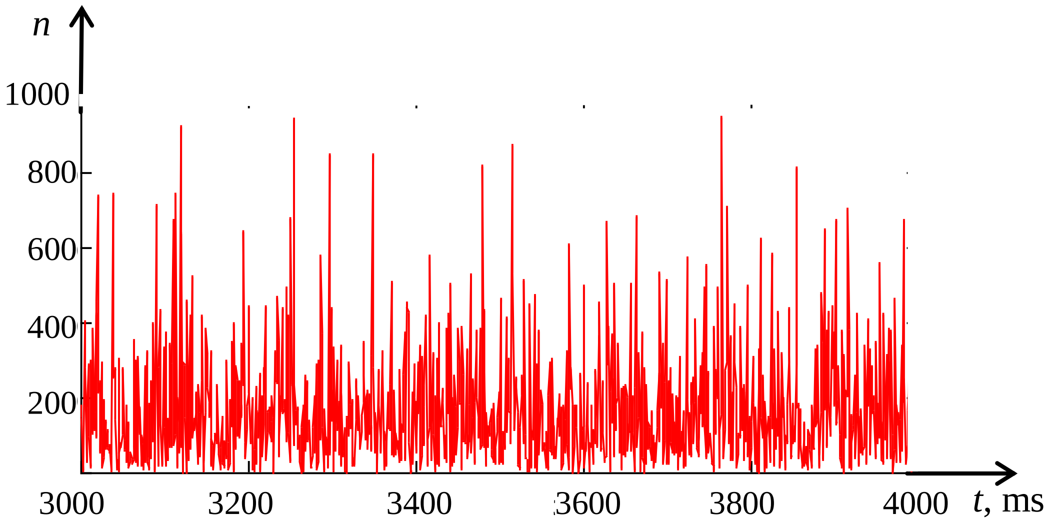

Figure 1 – The simulation results for self-similar traffic interval [3000, 4000] ms

Consider the spline extrapolation for simulated self-similar traffic on the interval [3000; 3050] ms, using the cubic B-spline $B_i(x)$ (Fig. 2).

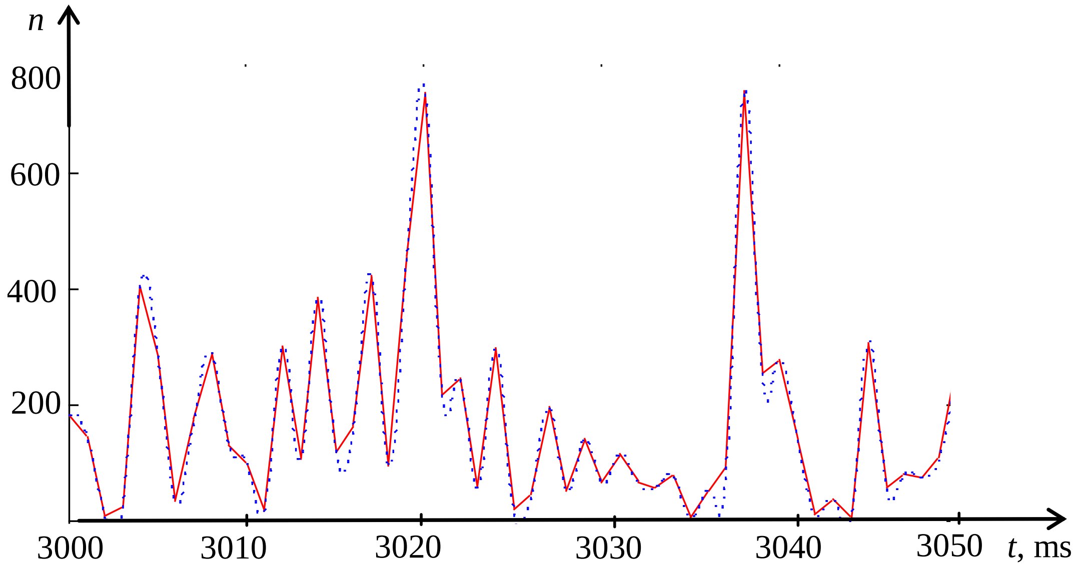

Figure 2 – The results of the extrapolation of self-similar traffic using a cubic B-spline on the segment [3000; 3050] ms

According to formula (14), we determine the spline-extrapolation error for self-similar traffic in the [3000; 3050] ms segment for given partial intervals $[x_i, x_{i+1}]$, $i = 0,1,\ldots, N$ (Tab. 1).

Table 1 – Values of prediction spline-extrapolation self-similar traffic

Interval	Numerical values of the interval	Error value
$[x_0;x_1]$	[3000;3001]	0,097
$[x_1;x_2]$	[3001;3002]	0,579
$[x_2;x_3]$	[3002;3003]	0,337
$[x_3;x_4]$	[3003;3004]	0,082
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End of Table 1

Interval	Numerical values of the interval	Error value
$[x_{23};x_{24}]$	[3023;3024]	0,121
$[x_{24};x_{25}]$	[3024;3025]	0,087
$[x_{25};x_{26}]$	[3025;3026]	0,146
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$[x_{42};x_{43}]$	[3042;3043]	0,546
$[x_{43};x_{44}]$	[3043;3044]	0,049
$[x_{44};x_{45}]$	[3044;3045]	0,123
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$[x_{47};x_{48}]$	[3047;3048]	0,912
$[x_{48};x_{49}]$	[3048;3049]	0,007
$[x_{49};x_{50}]$	[3049;3050]	0,027

Based on the results of traffic forecasting taking into account the maximum values of workloads of network nodes, practical recommendations can be given on the redistribution of traffic in the network. This will balance the load on the network facilities and more efficient use of network equipment.

CONCLUSIONS

1. The solution of the problem of predicting self-similar traffic using an extrapolation method based on cubic B-spline functions is considered.

2. Cubic B-splines have a high constructiveness, adequacy of the tasks and ease of practical implementation. Their use allows to make further simplification of computational procedures, using the formal mathematical constructions. At the same time, the amount of information stored in the calculation procedures is noticeably reduced, the amount of this information is (2N+5) numbers, while using ordinary cubic splines requires 3(N+1) numbers, where *N* is the number of interpolation nodes.

3. Using the proposed extrapolation method based on cubic B-splines has several advantages compared with the known methods: ease of implementation, high prediction accuracy, the ability to sufficiently accurately extrapolate peak traffic bursts, which is especially important when solving real-world traffic control problems timescale.

4. The results of the extrapolation of self-similar traffic based on cubic B-splines will allow to provide the required size of buffer devices, thereby avoiding network overloads and exceeding the standard values of QoS characteristics.

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