Methods of Spline Functions in Solving Problems of Telecommunication and Information Technologies

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Abstract: The solution to problems of telecommunications and information technologies using spline approximation and spline extrapolation based on real and complex spline functions is considered. The use of spline approximation for solving problems of signal recovery and self-similar traffic, processes of functioning of telecommunication nodes and networks is shown. It is proposed to use spline extrapolation based on various types of real spline functions to solve the problems of predicting the characteristics of self-similar traffic and maintaining QoS characteristics during its maintenance. It has been established that to predict the real-time telemetry traffic of IoT devices, it is advisable to use spline extrapolation based on the cubic Hermite spike, which ensures the required forecasting accuracy and prevents network overloads, especially under conditions of network load limit. To solve the problem of user positioning in the radio access area, the use of complex plane spline functions is considered. The use of the methods of real and complex spline functions allows for obtaining the results of improving the quality of service in a telecommunications network and ensuring the scalability of the obtained solutions. To identify and predict DDoS cyber-attacks, a spline extrapolation method is used. The use of parametric splines in the problems of information technology, namely, the construction of curves and surfaces in 3D modelling, is proposed.

1 INTRODUCTION

The rapid development of technology leads to changes in many technological solutions and the improvement of protocols and algorithms of systems and software. Such changes require reviewing existing solutions and searching for new methods of solving telecommunications and information technology problems [1-4]. The process of creating a theory of telecommunications and information technologies is not yet complete; however, engineering intuition is often ahead of science today and allows finding the necessary solutions to problems at the intersection of different sciences, thereby moving from purely technological solutions to solutions based on system theory [5-8].

The solution of many problems requires the search for effective tools for system analysis and synthesis of modern telecommunication and information systems based on new mathematical methods. A review of the known solutions suggests that they are based on several already-known mathematical methods, such as functional analysis, integral and differential calculus, group theory, operator theory, spectral analysis, and others [1-8]. It is important to find such mathematical methods, an alternative to the known ones, which will significantly simplify the solution process and at the same time provide new solution possibilities. Such a solution may be the use of spline function methods, such as spline approximation and spline extrapolation.

The studies carried out by the authors in [9-12], allow us to assert the advantage of using splines, because: splines are easy to calculate, have good convergence, are resistant to local disturbances, have scalability properties, and provide opportunities to ensure the required accuracy.

The use of interpolation, approximation, and extrapolation methods for processes and modes of network elements, as well as network functions, allows us to obtain solutions to a significant class of telecommunications problems using real and complex spline functions [9-14]. The use of real and complex spline functions has an important practical advantage - a fairly simple implementation and the possibility of almost universal use.

Paper [9] shows the recovery of signals using counts and compares the recovery results using the Kotelnikov series and spline approximation based on cubic splines. It is established that the use of spline approximation for a signal with frequency fluctuations allows for obtaining results with the smallest error.

The advantage of spline approximation in solving traffic restoration problems has been proven using various types of spline functions (linear, quadratic, cubic, B-splines, etc.) in [9-12].

At the present stage of telecommunications development, an important issue is to solve the problems of predicting the characteristics of traffic served in the network. For this purpose, works [10-11] propose the use of spline extrapolation based on various spline functions (linear, quadratic, quadratic B-splines, cubic, cubic B-splines and cubic Hermite splines), which allow to increase the accuracy of the forecast.

The forecasting results allow us to predict the required size of buffer devices and characteristics of network objects, thereby preventing network congestion and exceeding the standard values of QoS characteristics [11].

However, there are several problems that cannot be solved using real splines, such as positioning problems. When solving such problems, there is a need to determine the user's coordinates about the received signal strength.

In this case, the authors propose the use of complex plane spline functions, which allow for to reduction of the positioning error compared to other known methods [12].

Today, the IT industry needs a different approach to solving a significant number of tasks that require a reduction in computational complexity and calculation time, but have requirements for the accuracy of the results. For example, in 3D modelling, cybersecurity and information protection tasks [9-14].

The purpose of this paper is to find new methods for solving analysis and synthesis problems in information technology.

2 APPROXIMATION ON THE BASIS OF SPLINE FUNCTIONS IN PROBLEMS OF TELECOMMUNICATION AND INFORMATION TECHNOLOGIES

With the help of real spline functions (linear, quadratic, quadratic B-splines, cubic, cubic B-splines and cubic Hermite splines), several problems in telecommunications have been solved, namely:

- the restoration of random signals and self-similar traffic, the solutions of which allow obtaining the required values between interpolation nodes with the required error [9-10];
- management of network objects and the network as a whole, which are based on the results of network monitoring and data processing [11];
- support of the procedures for the operation of objects and the network as a whole to improve the quality characteristics of QoS/QoE operation [11].

2.1 The Problem of Restoring Continuous Signals Using Spline Approximation Based on Real Cubic Splines

Consider the problem of restoring a continuous signal $f(x)$ on the interval [0;1], which is given by a function of the form [9]:

$$f(x) = 2\frac{\sin(16\pi(x-\frac{1}{2}))}{16\pi(x-\frac{1}{2})} - 3\frac{\sin(8\pi(x-\frac{1}{2}))}{8\pi(x-\frac{1}{2})}, \quad (1)$$

using the Kotelnikov series and spline approximation. The original signal $f(x)$ is limited by the spectrum $F_{\max}$ = 8 kHz, the sampling step is. The recovery of the continuous signal $f(x)$ by the Kotelnikov series is shown in Figure 1.

Let us consider the recovery of the signal $f(x)$ using a spline approximation based on a real cubic spline. We use the samples of the original signal $f(x)$ as interpolation nodes.

Considering the signal $f(x)$ of the form (1) on the interval [0;1], we set the grid node partitioning Δ: $0 = x_0 < x_1 < ... < x_N = 1$.

To construct the cubic interpolation spline $S_3(x)$, we construct a cubic function on each of the intervals $[x_i, x_{i+1}]$, $i = 0, \ldots, n-1$.

The cubic spline $S_3(x)$ for $x \in [x_i, x_{i+1}]$, $i = 0, \ldots, n-1$ is as follows [9]:

$$S_3(x) = f_i(1-t)^2(1+2t) + f_{i+1}t^2(3-2t) + \\ + m_i h_i t(1-t)^2 - m_{i+1}h_i t^2(1-t), \quad (2)$$

moreover $t = (x - x_i)/h_i$, $S_3(x_i) = f_i$, $S_3(x_{i+1}) = f_{i+1}$, $m_i = S'(f; x_i)$, $h_i = h = (b-a)/n$, n – number of segment breakdown elements $[a,b]$.

The obtained recovery of the continuous signal $f(x)$ is shown in Figure 1. where line 1 is the original signal $f(x)$, line 2 is the value of the function $f(x)$ in the grid nodes, line 3 is the recovered continuous signal $f(x)$ using the Kotelnikov series, line 4 is the recovered signal $f(x)$ using the cubic spline approximation.

According to the results of the recovery of a continuous signal $f(x)$, it was found that the use of a spline approximation based on a cubic spline has a smaller error and can be used to recover various signals characterized by the presence of rapid oscillations [9].

Thus, it can be noted that in solving telecommunication problems, the use of spline approximation makes it easier to obtain solutions to a class of problems, such as restoring and estimating states (data, signals, traffic), signal and image processing tasks, including data filtering and compression, signal detection and measurement, and improving the QoS characteristics of telecommunication networks with the required accuracy.

2.2 The Problem of Spline Approximation of Curves and Surfaces Based on Real Parametric Linear Splines

Consider the task of creating curves and surfaces in 3D modelling. Spline curves and surfaces are used in animation, video games, and interactive applications. Creating the trajectory of objects in time, and deformation processes in response to user actions or changes in the environment is a complex and resource-intensive process. The mathematical apparatus of spline functions, which has been used in telecommunications applications, can help.

To solve modelling problems, namely, the construction of curves and surfaces, we use linear parametric splines.

When interpolating the curve given parametrically by (3), we divide the interval of change of the parameter u, thus $u_0 < u_1 < \ldots < u_N$.

Let us find the value of the function at the partition points u_i, $i = 0, N$ [15]:

$$\begin{cases} x_i = x(u_i); \\ y_i = y(u_i). \end{cases} \quad (3)$$

The interpolation parametric spline of the first degree on the interval between points P_i and P_{i+1} has the form [15]:

$$\begin{cases} S_1(x;s) = (1-t)x_i + tx_{i+1}; \\ S_1(y;s) = (1-t)y_i + ty_{i+1}. \end{cases} \quad (4)$$

where $t = (s - s_i)/l_i$, $l_i = s_{i+1} - s_i$, $i = 0, 1, \ldots, N-1$.

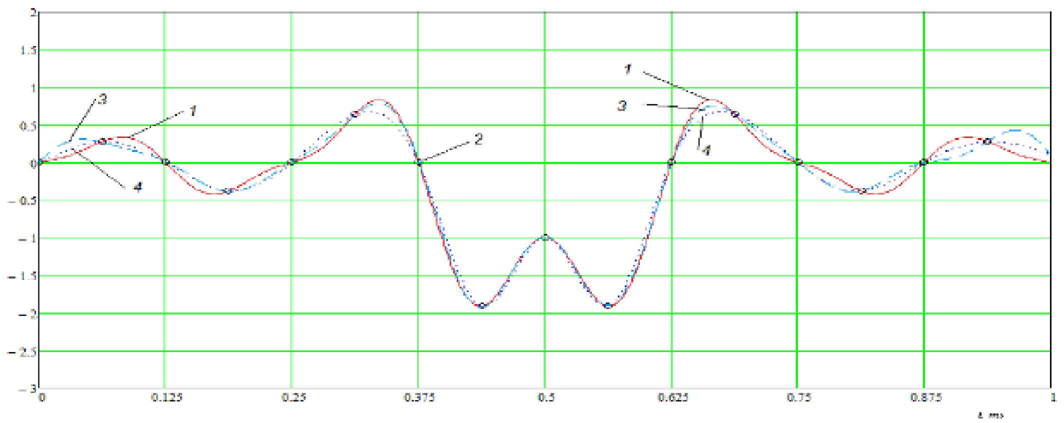

Figure 1: Restoration of a continuous signal $f(x)$ using the Kotelnikov series and spline approximation based on the cubic spline.

The set of splines $S_1(x;u)$ and $S_1(y;u)$ are a linear interpolation parametric spline. Depending on the type of function, linear parametric quadratic, cubic and other splines are considered [15].

An example of the construction of a linear parametric spline of the form (4) for a given curve L is shown by the dashed line in Figure 2.

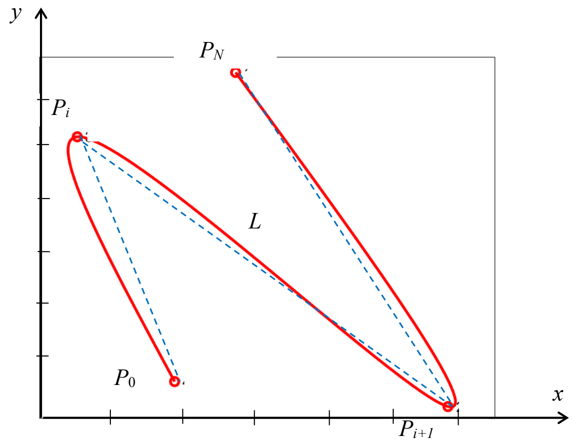

Figure 2: Approximation of a plane curve by a linear parametric spline.

It is easy to see that such a curve has significant errors of up to 25 %, which can be reduced by reducing the interpolation step.

To reduce the error in the reproduction of curves and surfaces, it is possible to use higher-order splines, such as quadratic, cubic, or cubic B-splines.

2.3 The Problem of Spline Approximation Based on Complex Plane Splines

To determine the location of a user in a Wi-Fi/Indoor network, we will consider spline approximation [12-13], [16-18]. We will use a complex plane quadratic spline as an approximating function [12], [19-20].

Consider a Wi-Fi/Indoor network (Figure 3), which consists of a set of AP_i, where i is the number of AP_i, $i=\overline{1,3}$.

Define the coverage area of the Wi-Fi/Indoor network by $\overline{G}$, for which $\overline{G}\subset Q$ (Figure 4), where $Q=[a,a+H]\times[b,b+H]$ with the side $H>0$ and a step $h_N=\frac{H}{N}$, N is a natural number, $x_k=a+kh_N$, $y_j=b+jh_N$, $k,j=0,1,\ldots,N$.

Moreover, $\overline{G}=G\cup\partial G$ where ∂G is the boundary of the domain G. Let's break down the coverage area of the Wi-Fi/Indoor network into segments $Q_{k,j}$,.

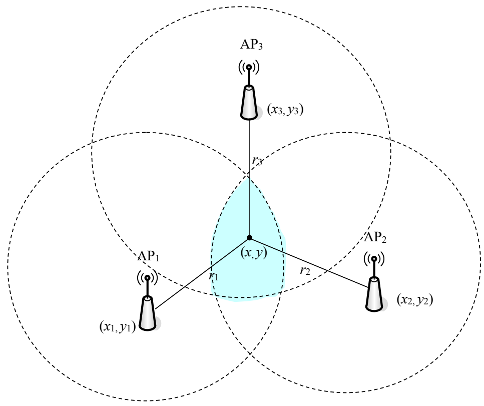

Figure 3: Wi-Fi/Indoor network.

Then $Q=\bigcup_{k,j=0}^{N-1}Q_{k,j}$,

$$Q_{k,j}=\left\{z=x+iy : x\in[x_k,x_{k+1}]\ ,y\in[y_j,x_{j+1}]\right\}.$$

This partition is denoted by Δ_N.

We define the domain G_N as the union of all segments $Q_{k,j}$ for which $Q_{k,j}\cap G\neq\varnothing$.

To find the coordinates of the user's location, consider one of the partitioning elements that are part of the G_N region with vertices P_1, P_2, P_3, and P_4, for which the following conditions are met (Figure 4) [12], [19-20]:

$$\operatorname{Re} P_1=\operatorname{Re} P_4,\ \operatorname{Re} P_2=\operatorname{Re} P_3,$$
$$\operatorname{Im} P_1=\operatorname{Im} P_2,\ \operatorname{Im} P_3=\operatorname{Im} P_4. \quad (5)$$

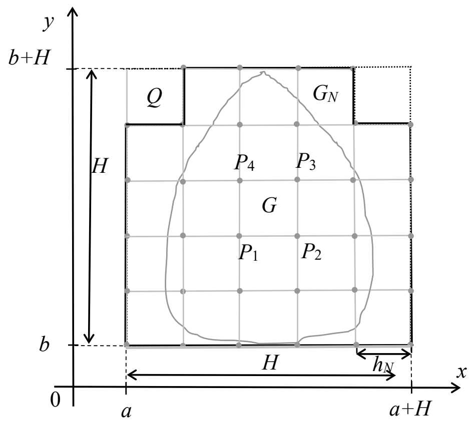

Figure 4: G_N area.

Let us construct a quadratic flat complex spline $S_\Delta(z)$, on the grid domain G_N that interpolates the function f(z) (or its continuation) at the vertices of the rectangles $Q_{k,j}$ included in the domain G_N, considering [12], [19-20]:

$$S_\Delta(z) = a + bz + c\bar{z} + d(z^2 - \bar{z}^2), \qquad (6)$$

at $z \in Q_{k,j} \subset G_N$, where the coefficients a, b, c, d are determined from the interpolation conditions at the $z_{k,j} = x_k + iy_j$:

$$S_\Delta(z_{k,j}) = f(z_{k,j}), \quad S_\Delta(z_{k+1,j}) = f(z_{k+1,j}),$$
$$S_\Delta(z_{k,j+1}) = f(z_{k,j+1}), \quad S_\Delta(z_{k+1,j+1}) = f(z_{k+1,j+1}).$$

The function $S_\Delta(z)$ is continuous in G_N [19-20].

3 EXTRAPOLATION ON THE BASIS OF SPLINE FUNCTIONS IN TELECOMMUNICATION AND INFORMATION TECHNOLOGIES

Spline extrapolation methods based on real spline functions of linear, quadratic, quadratic B-splines, cubic, cubic B-splines and cubic Hermite splines [15], [20] have allowed solving a significant class of problems in telecommunications and information technology:

- prediction of traffic characteristics, the solution of which in real time for different types of traffic (data traffic, voice traffic, telemetry traffic and video streaming traffic) provides opportunities to support QoS characterristics [11];
- support of QoS quality characteristics, namely, characteristics of delay time and probability of packet loss and distortion when servicing different types of traffic and forming requirements for network buffer devices [11];
- selection of the optimal configuration of telecommunication network objects, the decision of which is based on the results of forecasting the characteristics of the traffic of objects and the network as a whole to improve the quality of the telecommunication network [10-11];
- determination and forecasting of DDoS-type cyberattack traffic (SYN-Flood, ICMP-Flood, UDP-Flood) using splines [14].

3.1 The Task of Predicting the Characteristics of IoT Device Telemetry Traffic Using Spline Functions

When solving the problem of predicting the characteristics of the real-time telemetry traffic of an IoT (Internet of Things) device, it is taken into account that the traffic is created by sensors that operate according to a schedule and have functional features that determine the functioning of the system as a response to data requests to the sensors.

For forecasting, we use spline extrapolation based on the Hermite cubic spline [15], [20].

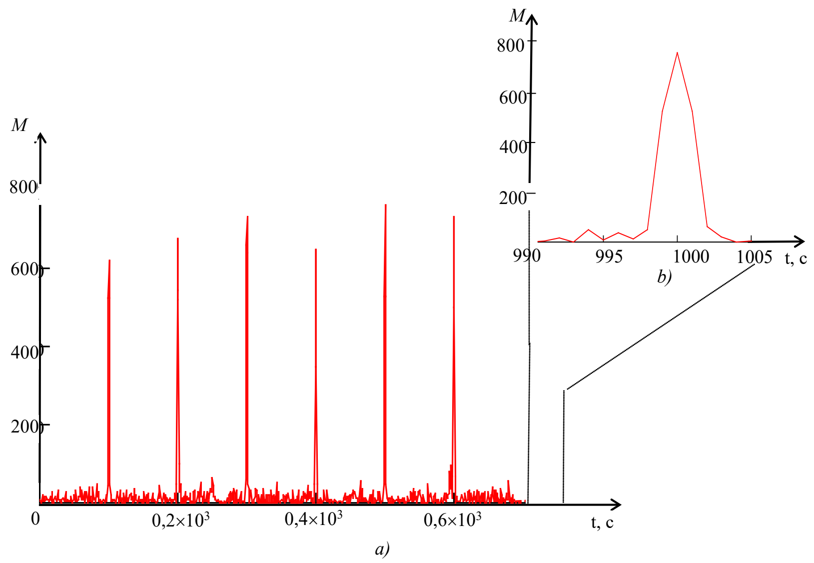

Figure 5: Real-time telemetry traffic of an IoT device, *a*) real traffic at [1;990] s, *b*) forecast traffic at [990;1005] s.

Consider the traffic of an IoT device on the segment $[a;b]$. To do this, let's break down $[a;b]$ as follows Δ: $a = x_0 < x_1 < \ldots < x_n = b$.

The nodes x_i contain the value of the function $f(x)$ and its derivative $f'(x)$, where $f_i = f(x_i)$, $f'_i = f'(x_i)$, $i = 0, 1, \ldots, n$.

Let's use the Hermite cubic spline $S_{3,2}(f;x) = S_{3,2}(x)$, that meets the conditions of [15], [20]:

- at each of the segments $[x_i; x_{i+1}]$, $i = 0,.., n-1$,

  $$S_{3,2}(x) = a_{io} + a_{i1}(x-x_i) + a_{i2}(x-x_i)^2 + a_{i3}(x-x_i)^3;$$

- function $S_{3,2}(x_i) = f_i$, $S'_{3,2}(x_i) = f'_i$, $i = 0, \ldots, n$.

The Hermite cubic spline has the form [15], [20]:

$$S_{3,2}(x) = \varphi_1(t) f_i + \varphi_2(t) f_{i+1} + \varphi_3(t)\, h_i f'_i + \varphi_4(t)\, h_i f'_{i+1}, \quad (7)$$

moreover $\varphi_1(t) = (1-t)^2(1+2t)$, $\varphi_2(t) = t^2(3-2t)$, $\varphi_3(t) = t(1-t)^2$, $\varphi_4(t) = -t^2(1-t)$, $h_i = x_{i+1} - x_i$, $t = (x - x_i)/h_i$, $i = 0, \ldots, n$.

The telemetry traffic of an IoT device is shown in Figure 5, where M is the number of packets (thousand packets).

The results of spline extrapolation of the traffic on the segment [990;1005] ms using the Hermite cubic spline $S_{3,2}(x)$ of the form (7) are shown in Figure 6.

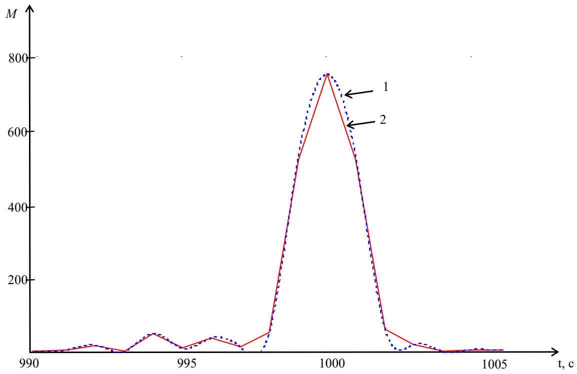

Figure 6: Predicting IoT device telemetry traffic using spline extrapolation based on the Hermite cubic spline: line 1 is real IoT device traffic, line 2 is predicted using spline extrapolation.

The obtained results of predicting the characteristics of the IoT device's real-time telemetry traffic allow for predicting the required IoT device bandwidth, as well as preventing congestion, which will ensure the maintenance of the required QoS characteristics.

3.2 The Task of Detecting and Predicting DDoS Cyberattack Traffic Using Spline Functions

When considering the characteristics of DDoS (Distributed Denial of Service) traffic, periodic or non-periodic, short and significant "bursts" of traffic intensity are often noted, while legitimate traffic has a small amplitude of pulsations that occur over a long period [21-30].

Given that cyberattack traffic has self-similarity properties, spline extrapolation can be used to solve the problems of detecting and predicting DDoS attacks (SYN-Flood, ICMP-Flood, UDP-Flood) [23-27]. We use the spline extrapolation method to predict the traffic of DDoS cyberattacks (Figure 7) [28-30].

To construct the cubic interpolation spline $S_3(x)$, we use the approach given in Section 2.1 and the expression of the cubic spline (2), for which we use the boundary conditions [15]:

$$S'(f;a) = f'(a),\ \ S'(f;b) = f'(b). \quad (8)$$

Considering the traffic on the segment $[a;b]$, we set a uniform partitioning grid with a step $h_i = h$, $i = 0, 1, \ldots, n-1$, $h = \frac{b-a}{n}$. To build a cubic spline, we use the values of traffic intensities set at the interpolation nodes x_i, $i = 0, 1, \ldots, n$.

By constructing a cubic interpolation spline of the form (2) on the segment $[a;b]$, we obtain the required extrapolated values.

The proposed spline extrapolation based on spline functions has several advantages over the known methods. It is quite simple to implement, has a smaller error in predicting cyberattack traffic, and can be used to identify and predict DDoS traffic in real-time.

A successful choice of the type of spline functions when performing spline extrapolation can improve the accuracy of DDoS attack traffic detection. Prospects for further research are to further improve the accuracy of determining and predicting the traffic characteristics of various DDoS cyberattacks (SYN-Flood, ICMP-Flood, UDP-Flood) using the wavelet extrapolation method with an appropriate choice of wavelet functions [14].

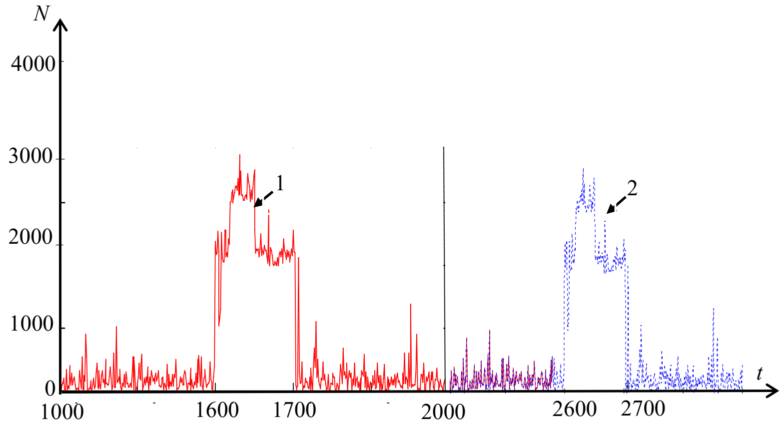

Figure 7: Results of extrapolation of DDoS cyberattack traffic on the segment [2600;2700] using a cubic spline: line 1 is DDoS attack traffic, line 2 traffic extrapolation using a cubic spline.

4 CONCLUSIONS

1) Along with solving telecommunications problems using spline approximation, spline approximation and spline extrapolation are proposed and used in cybersecurity problems, which can significantly simplify the solution process and at the same time provide new opportunities for obtaining results.

2) The use of spline approximation is proposed, which makes it easier to obtain solutions to such problems as restoration and estimation of states (data, signals and traffic), signal and image processing tasks, including the tasks of improving the quality characteristics of QoS of telecommunication networks.

3) A spline extrapolation method has been developed that allows us to obtain solutions to the problems of predicting traffic characteristics, identifying and predicting DDoS attacks, and improving the accuracy of the forecast, ensuring the scalability of solutions.

4) The obtained results of forecasting IoT device telemetry traffic allow to improve the accuracy of the forecast and ensure its scalability and use for various IoT applications, thereby avoiding network overloads and exceeding the normative values of QoS characteristics.

5) It is determined that for solving positioning problems it is advisable to use complex plane splines, which make it possible to simplify the determination of the user's location coordinates in the radio access network and increase the positioning accuracy.

6) The use of linear parametric splines is proposed for modelling curves and surfaces. It has been established that interpolation of curves and surfaces in 3D modelling using parametric splines has a higher accuracy of building curves and surfaces compared to other methods of restoring these curves and surfaces.

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