UDK 621.391

USE OF SPLINE-EXTRAPOLATION TO IMPROVE THE QUALITY INDICATORS OF TELECOMMUNICATION SYSTEMS

Strelkovskaya I., Solovskaya I., Tolmak V.

O.S. Popov Odesa National Academy of Telecommunications,
1 Kuznechna St., Odesa , 65029, Ukraine.
strelkovskaya@onat.edu.ua, i.solovskaya@onat.edu.ua, tolmakvova@gmail.com

ВИКОРИСТАННЯ СПЛАЙН-ЕКСТРАПОЛЯЦІЇ ДЛЯ ПІДВИЩЕННЯ ПОКАЗНИКІВ ЯКОСТІ ТЕЛЕКОМУНІКАЦІЙНИХ СИСТЕМ

Стрелковська І.В., Соловська І.М., Толмак В.Є.

Одеська національна академія зв'язку ім. О.С. Попова,
65029, Україна, м. Одеса, вул. Кузнечна, 1.
strelkovskaya@onat.edu.ua, i.solovskaya@onat.edu.ua, tolmakvova@gmail.com

ИСПОЛЬЗОВАНИЕ СПЛАЙН-ЭКСТРАПОЛЯЦИИ ДЛЯ ПОВЫШЕНИЯ ПОКАЗАТЕЛЕЙ КАЧЕСТВА ТЕЛЕКОММУНИКАЦИОННЫХ СИСТЕМ

Стрелковская И.В., Соловская И.Н., Толмак В.Е.

Одесская национальная академия связи им. А.С. Попова,
65029, Украина, г. Одесса, ул. Кузнечная, 1.
strelkovskaya@onat.edu.ua, i.solovskaya@onat.edu.ua, tolmakvova@gmail.com

Abstract. The problem of predicting self-similar traffic with significant and frequent ripples and the property of long-term dependence is considered. For short-term prediction of self-similar traffic, which is performed outside the considered time interval, a method of spline extrapolation based on various spline functions (cubic and cubic B-splines) is proposed. We recommend a method for estimating traffic prediction errors for each traffic prediction option using cubic or cubic B-splines. Comparison of the results of predicting self-similar traffic using various spline functions (cubic and cubic B-splines) show that the accuracy of the prediction can be improved by using cubic B-splines. According to the results of the study, it is established that cubic B-splines are characterized by high constructively, adequacy to the tasks and simplicity of practical implementation. Their use makes it possible to greatly simplify computational processes using formalized mathematical constructs. 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 results of predicting self-similar traffic will allow the operator, at the stage of design and further operation of the mobile communication network, to provide the required amount of buffer devices for the network hardware and software, thereby avoiding network congestion and exceeding standard values of traffic service quality indicators. Proposed is the prospect of further research through the use of wavelet-extrapolation in order to improve the accuracy of prediction. Practical significance is determined by the developed recommendations for using the spline-extrapolation method in solving various problems of designing networks of various technologies and structures.

Key words: self-similar traffic, quality of service, predicting, extrapolation, spline function

Анотація. Розглянуто задачу прогнозування самоподібного трафіка, що має значні і часті пульсації та властивість довгострокової залежності. Для короткострокового прогнозу самоподібного трафіка, який виконується поза розглядуваного проміжку часу, запропонований метод сплайн-екстраполяції на базі різних сплайн-функцій (кубічних і кубічних В-сплайнів). Рекомендований метод оцінки похибки прогнозування трафіка для кожного варіанта прогнозування трафіка з використанням кубічних або кубічних В-сплайнів. Порівняння результатів прогнозування самоподібного трафіка з використанням різних сплайн-функцій (кубічних і кубічних В-сплайнів) дозволили довести, що точність прогнозу може бути підвищена за рахунок використання кубічних В-сплайнів. За результатами дослідження встановлено, що кубічні В-сплайни характеризуються високою конструктивністю, адекватністю до поставлених завдань та простотою практичної реалізації. Їх використання дозволяє значно спростити обчислювальні процеси, використовуючи формалізовані математичні конструкції. Використання запропонованого методу сплайн-екстраполяції має низку переваг порівняно з іншими відомими методами, а саме, простота практичної реалізації, висока точність прогнозу, можливості достатньо точно екстраполювати пікові «сплески» трафіка, що особливо важливо при вирішенні завдань в реальному масштабі часу. Результати прогнозування самоподібного трафіка 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 показників якості обслуговування трафіка. Запропоновано перспективу подальших досліджень за рахунок використання вейвлет-екстраполяції з метою підвищення точності прогнозування. Практична значимість визначається розробленими рекомендаціями для використання методу сплайн-екстраполяції при вирішенні різних завдань проектування мереж різних технологій та структур.

Ключові слова: самоподібний трафік, якість обслуговування, прогнозування, екстраполяція, сплайн-функція.

Аннотация. Рассмотрена задача прогнозирования самоподобного трафика, обладающего значительными и частыми пульсациями и свойством долгосрочной зависимости. Для краткосрочного прогноза самоподобного трафика, который выполняется вне рассматриваемого промежутка времени, предложен метод сплайн-экстраполяции на базе различных сплайн-функций (кубических и кубических В-сплайнов). Рекомендован метод оценки погрешности прогнозирования трафика для каждого варианта прогнозирования трафика с использованием кубических или кубических В-сплайнов. Сравнение результатов прогнозирования самоподобного трафика с использованием различных сплайн-функций (кубических и кубических В-сплайнов) позволили показать, что точность прогноза может быть повышена за счет использования кубических В-сплайнов. Согласно результатам исследования установлено, что кубические В-сплайны характеризуются высокой конструктивностью, адекватностью к поставленным задачам и простотой практической реализации. Их использование позволяет значительно упростить вычислительные процессы, используя формализованные математические конструкции. Использование предложенного метода сплайн-экстраполяции имеет ряд преимуществ в сравнении с другими известными методами, а именно, простота практической реализации, высокая точность прогноза, возможности достаточно точно экстраполировать пиковые «всплески» трафика, что особенно важно при решении задач в реальном масштабе времени. Результаты прогнозирования самоподобного трафика позволят оператору на этапе проектирования и дальнейшей эксплуатации сети мобильной связи предусмотреть требуемый объем буферных устройств аппаратно-программных средств сети, тем самым избежав перегрузок в сети и превышений нормативных значений показателей качества обслуживания трафика. Предложено перспективу дальнейших исследований за счет использования вейвлет-экстраполяции с целью повышения точности прогнозирования. Практическая значимость определяется разработанными рекомендациями для использования метода сплайн-экстраполяции при решении различных задач проектирования сетей различных технологий и структур.

Ключевые слова: самоподобный трафик, качество обслуживания, прогнозирование, экстраполяция, сплайн-функция.

The development of fifth generation 5G/NR mobile networks (New Radio) primarily involves the introduction of a new range of services for users. These are video service Video Surveillance, Smart-TV, IoT-cameras, smart-M2M objects services, IoT-telemetry services, IoT-telemedicine telemedicine services, Smart house systems, Smart house, Smart parking lots, Smart grids and, in perspective, holographic TV, virtual VR (Virtual reality) services and augmented AR (Augmented reality) realities [1-2].

The development of these services requires the operator, first of all, to increase the data transfer speed and provide the required values of the quality of service traffic. The traffic served on the IoT network is quite heterogeneous. It has different indicators depending on each type of service. At times it is low-speed data transfer by IoT sensors, and at times real-time HD video transmission.

It is known [3] that the high-speed data traffic that is generated by the IoT network objects is self-similar. This is determined by the long-term relationship between traffic values at different time periods, significant and frequent bursts of intensity, which are statistically similar for different time scales. In practice, the appearance of long-term traffic pulsations at arbitrary points in time often leads to a sharp increase in packet delay time, which causes congestion of network nodes and buffer devices and, accordingly, has a significant impact on the quality of traffic service [3]. Predicting the characteristics of self-similar traffic will allow for possible peak loads in the network and efficient traffic management, thereby ensuring the required quality indicators. Given the above facts, the urgency of the task of predicting self-similar traffic is obvious.

The aim of the work is to solve the problem of predicting self-similar traffic and choosing a method by which traffic will be restored more accurately outside the considered interval, on which traffic is defined.

In predicting the indicators of self-similar traffic, which is determined on a given interval of consideration by a certain function, the extrapolation of the function is used, which allows obtaining the continuation of the function outside its domain of definition using information about the behavior of the function in the extrapolation nodes belonging to its domain of definition. The spline extrapolation method has several advantages over the currently known extrapolation methods: resistance to local disturbances, good convergence of spline interpolation, in particular, for functions with irregular smoothness properties (an example of which is self-similar traffic), spline has an undeniable priority -interpolation.

A significant number of scientific papers [5–15] have been devoted to the issues of predicting self-similar traffic, in which the authors proposed various predicting methods. A “classical” approach to predicting traffic characteristics was used in [4], where various extrapolation methods were compared (Lagrange polynomial, Markov chains, automaton method) and the expediency of using the extrapolation method to predict self-similar traffic was shown. One of the generally accepted traffic predicting mechanisms is the linear regression models ARIMA and FARIMA, considered in [5–7]. However, their use is recommended for traffic with weak self-similarity, which is difficult to attribute to the traffic considered in this work. The neural network predicting method considered in [8–9] allows one to solve several of practical predicting problems, such as dynamically redistributing the bandwidth in order to use network resources and support quality characteristics.

However, it is important to note that the use of the neural network method implies the need for network training, it is a complex and time-consuming process, and even a “trained” network is not always clearly predictable due to heuristic approaches in its construction. The prediction accuracy in such a network depends on the number of training options, and the implementation has high requirements for computing capabilities. In work [10], the author, in comparing the results of predicting network traffic with the help of the linear regression model of SARIMA and neural networks, showed that in most cases the use of complex and time-consuming methods of neural networks is impractical.

Review of the literature in the field of prediction of self-similar traffic characteristics leads to the conclusion about the complexity of the known methods of predicting and achieving prediction accuracy. This significantly reduces the scope of their practical use, especially in predicting in real time for networks with a large bandwidth. The extrapolation methods considered by the authors [4–10] are, as a rule, laborious, have significant errors under conditions of frequent and significant bursts of traffic intensity, and are difficult to implement in predicting traffic in real time. The solution of the problem of extrapolation by cubic splines or piecewise polynomial representation of them in many cases is a convenient tool in the computational sense [11-13]. Consider the spline extrapolation method for self-similar traffic, which is modeled in the Simulink package of the Matlab environment using various spline functions (cubic and B-splines).

Method of Self-Similar Traffic Prediction. Consider self-similar traffic in a segment $[a;b]$. Let a partition Δ: $a = x_0 < x_1 < \ldots < x_N = b$ be given on a segment $[a;b]$. Consider a cubic interpolation spline $S_3(x)$, for which at each interval $[x_i; x_{i+1}]$, $i = 1, \ldots, N-1$ it will be a cubic function. According to [14], for $x \in [x_i; x_{i+1}]$, $i = 0, 1, \ldots, N-1$ the cubic spline has the form:

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

where $t = \dfrac{x - x_i}{h_i}$; $S_3(x_i) = f_i$; $S_3(x_{i+1}) = f_{i+1}$; $S''(x_i) = M_i$; $S''(x_{i+1}) = M_{i+1}$; $h_i = x_{i+1} - x_i$, $x \in [x_i; x_{i+1}]$; $i = 1,...,\ N-1$.

To determine the cubic spline of the form (1), boundary conditions of the form are used [14]:

$$S^{(r)}(f;a) = S^{(r)}(f;b),\ r = 1,\ 2. \qquad (2)$$

Let us consider the uniform partition of the interval $[a;b]$, i.e.

$$h_i = h = \frac{b-a}{N},\ i = 0,1,...,N-1.$$

Supplement the grid $\Delta: a = x_0 < x_1 < ... < x_N = b$ with the nodes $x_{-3} < x_{-2} < .x_{-1} < a$, $b < x_{N+1} < .x_{N+2} < x_{N+3}$. Consider a cubic B-spline that is different from zero on the interval $(x_{i-2,} x_{i+2})$. It is convenient to number B-splines of odd degrees by the middle node of their carrier intervals. The desired B-spline will be denoted by $B_i(x)$. Put $y_p = B_i(x_p)$, $M_p = B_i''(x_p)$. As for any cubic spline, $B_i(x)$ hold the following equations [14]:

$$\mu_p M_{p-1} + 2M_p + \lambda_p M_{p+1} = \frac{6}{h_{p-1} + h_p}\left(\frac{y_{p+1} - y_p}{h_p} - \frac{y_p - y_{p-1}}{h_{p-1}}\right), \qquad (3)$$

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

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

$$B_i^{(r)}(x_{i-2}) = B_i^{(r)}(x_{i+2}) = 0,\ r = 0,\ 1,\ 2. \qquad (4)$$

Considering that for B-spline the relation [14]:

$$B_i(x) = y_i(1-t) + y_{i+1}t - \frac{h_i^2}{6}t(1-t) \times [(2-t)M_i + (1+t)M_{i+1}], \qquad (5)$$

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

we get

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

$$B_i''(x) = M_i(1 - t) + M_{i+1}t. \quad (7)$$

Then conditions (4), due to equalities (5-7), can be represented by the equalities:

$$\begin{cases} y_{i-2} = y_{i+2} = 0,\ M_{i-2} = M_{i+2} = 0, \\ y_{i-1} = \frac{1}{6}h_{i-2}^2 M_{i-1},\ \ y_{i+1} = \frac{1}{6}h_{i+1}^2 M_{i+1}. \end{cases} \quad (8)$$

According to [14], it is not difficult to find the error in recovering self-similar traffic on a segment $[b; x_c]$ using cubic spline functions.

Theorem 1. [14] If $f(x) \in C\,[a;b]$ and $S_3(x)$ satisfies the boundary conditions (2) then

$$\|S(x) - f(x)\|_C \le \left\{1 + \frac{3}{4}\frac{\varphi^{n+1}(\varphi + \varphi^{-1/n})}{2(1+\varphi) - \varphi^3 - \sqrt[n]{\varphi}}\right\}\omega(f), \quad (9)$$

where n – positive integer; $\varphi < \varphi^*$, φ^* – positive root of the equation; $2\varphi(1+\varphi) - \varphi^3 - \sqrt[n]{\varphi} = 0$; $\omega(f) = \omega_i(f;h) = \max\limits_{\substack{x',x'' \in [a,b] \\ |x''-x'| \le h}} |\ f(x'') - f(x')\ |$ – function continuity module $f(x)$.

According to Theorem 1, we find the error in extrapolating self-similar traffic to a cubic B-spline.

Experiments. Consider spline extrapolation of self-similar traffic using various spline functions. As splines we will consider cubic and cubic B-splines.

We simulate self-similar traffic for the queuing system (QS) W_B/M/1/K on the interval [3000; 4080] ms with the following parameters: λ − packet arrival rate for service in the QS; λ = 140 pack/s; μ − packet serving duration; μ = 140 pack/s; К − packet queue length, К=1000 packets; Hurst parameter H = 0,7; Weibull distribution parameters $\alpha \approx 0{,}6$ and $\beta \approx 24{,}781$. The results of modeling self-similar traffic in the Simulink package of the Matlab environment for the given source data are shown in Fig. 1, where *k* is the number of packets, *t* is the time of arrival of packets [11-13]. A high value of the Hurst parameter is accompanied by a high traffic burden and the presence of significant and frequent bursts of traffic intensity, which is observed in Fig. 1.

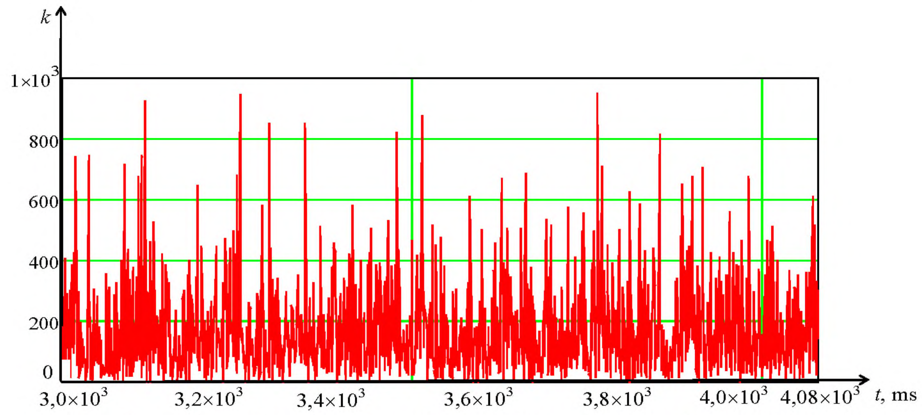

Figure 1 – The results of modelling self-similar traffic

According to Fig. 1, for the obtained self-similar traffic on the interval [3000;4080] ms, there is a large-scale invariance, a significant number of “bursts” of traffic intensity and a long-term relationship between the moments of their arrival. Let us consider the extrapolation of traffic over the interval [4070;4080] ms and compare with the results of modeling self-similar traffic. From Fig. 1 we can see that for the obtained self-similar traffic on the interval [3000;4080] ms, there is a large-scale traffic invariance, the presence of bursts of packets and a long-term relationship between the moments of their arrival. It is the presence of a significant number of frequent “bursts” of traffic intensity that leads to a sharp increase in packet delay time, which causes congestion of network nodes and buffer devices and, accordingly, has a significant impact on the quality of traffic service.

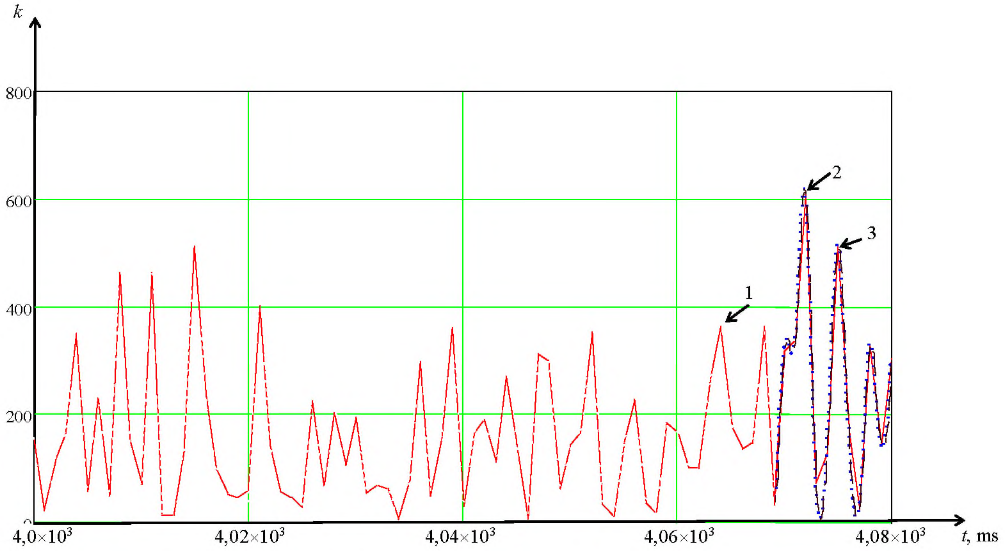

Figure 2 – Comparison of the results of extrapolation of self-similar traffic using cubic and cubic B-spline for the interval [4070; 4080] ms: 1 – self-similar traffic; 2 – extrapolation of self-similar traffic using a cubic spline function; 3 – extrapolation of self-similar traffic using a cubic B-spline

Using the results obtained by the authors using cubic splines in [12–13], we consider the use of a cubic B-spline to extrapolate simulated self-similar traffic over the interval [4070;4080] ms, the results of which are shown in Fig. 2.

The errors in reconstructing self-similar traffic using a cubic B-spline were estimated using Theorem 1 and are summarized in Table 1.

Table 1 – Errors of recovery of self-similar traffic using linear, cubic and cubic B-spline

Line segment	Numerical interval values, ms	Error of recovery based on a cubic spline	Error of recovery based on a cubic B- spline
…	…	…	…
$[x_{70}; x_{71}]$	$[x_{4070}; x_{4071}]$	22,3	8,3
$[x_{71}; x_{72}]$	$[x_{4071}; x_{4072}]$	16,4	6,2
$[x_{73}; x_{74}]$	$[x_{4072}; x_{4073}]$	8,7	4,3
$[x_{74}; x_{75}]$	$[x_{4074}; x_{4075}]$	7,9	2,8
…	…	…	…

It is easy to see that the use of cubic spline functions has an error, which most often appears on extrapolation segments, where traffic intensity graphs have periodic “bursts” (Table 1). Moreover, it is easy to see in Fig. 2, that the error is noted on segments with significant periodic "bursts" of traffic [12-13]. It is possible to increase the accuracy of predicting traffic characteristics using the spline extrapolation method based on cubic B-splines.

The use of cubic B-splines allows achieving a reduction in error compared to the use of cubic splines, as shown in the Tab. 1. In general, the use of cubic B-splines allows predicting traffic parameters and almost completely restoring the "path" of self-similar traffic.

In this case, the traffic prediction is short-term in the interval [4070;4080] ms. Therefore, under the given traffic predicting conditions, the use of cubic spline-functions does not seem appropriate to the authors, since it does not allow to provide the required accuracy of the short-term prediction. In practice, short-term predictions are used in traffic management and routing, and decisions are made in real time, which leads to a decrease in QoS quality characteristics, especially for high-speed data and high-definition video traffic.

Conclusions:

1. An extrapolation method based on spline functions (cubic and cubic B-splines) is proposed. Using the method of spline extrapolation allowed us to predict self-similar traffic outside the considered period of time using the approximating apparatus of spline functions.

2. Estimates of the error in traffic recovery are obtained. The results of predicting self-similar traffic using spline functions show that predicting accuracy can be improved by using cubic B-splines.

3. The practical significance of the obtained results lies in the fact that the obtained results of predicting self-similar traffic will make it possible to provide the required volume of buffer devices, thereby avoiding network congestion and exceeding the standard values of QoS indicators.

4. Based on the results of traffic predicting under the condition of maximum network nodes, practical recommendations can be made on the redistribution of traffic in an IP network, for example, the TCP/IP protocol. Reducing the delay time compared to the TCP protocol allows the protocol without guaranteed UDP delivery. However, it is rather difficult to provide the required QoS quality indicators using only the UDP/TCP transport protocol, since the causes of the delays are mostly at the network level. Using the proposed method of spline extrapolation will allow predicting traffic characteristics, balancing the loading of network objects and increasing the efficiency of using network equipment.

REFERENCES:

1. 3rd Generation Partnership Project. "Study on Scenarios and Requirements for Next Generation Access Technologies", ETSI TR 38.913, V14.3.0, 2017. Access mode: https://www.etsi.org/deliver/etsi_tr/138900_138999/138913/14.02.0060/tr_138913v140 200p.pdf
2. 3rd Generation Partnership Project. "Study on Architecture for Architecture for Next Generation System", TR 23.799 V14.0.0, 2016. Access mode: https://portal.3gpp.org/ desktopmodules/Specifications/ SpecificationDetails.aspx?specification Id=3045
3. Kryilov V.V. Teoriya teletrafika i ee prilozheniya / V.V. Kryilov, S.S. Samohvalova. – SPb.: BHV-Peterburg, 2005. – 288 s.:il.
4. Sarigiannidis P. Predicting Multimedia Traffic in Wireless Networks: A Performance Evaluation of Cognitive Techniques / Sarigiannidis P., Aproikidis K., Louta M., Angelidis P. // Proceedings of the 5th International Conference on Information, Intelligence, Systems and Applications (IISA-2014), (7-9 July 2014), Chania, Greece, 2014. – P. 341-346. doi: 10.1109/IISA.2014.6878802
5. Kumar V. Short-term traffic flow prediction using seasonal ARIMA model with limited input data / Kumar V.,Vanajakshi L. // European Transport Research Review, Springer. – 2014. – Vol. 7-21, P. 9-21. doi: 10.1007/s12544-015-0170-8
6. Li C. A novel Self-Similar Traffic Prediction Method Based on Wavelet Transform for Satellite Internet / Li C., Han Y., Sun Z., Wang Z // EAI Endorsed Transactions on Ambient System. – 2017. – Vol. 4, Is. 14, P. 1–7. doi:10.4108/eai.28-8-2017.153306
7. Aldhyani Theyazn H. H. An Integrated Model for Prediction of Loading Packets in Network Traffic / Aldhyani Theyazn H. H., Manish R., Joshi / Proceedings of the Second International Conference on Information and Communication Technology for Competitive Strategies. (4-5 March), Udaipur: India, 2016. – P. 1–8. doi: 10.1145/2905055.2905236

8. Oravec M. Video Traffic Prediction Using Neural Networks / Oravec M., Petras M., Pilka P. // Acta Polytechnica Hungarica. – 2008. – Vol. 5, № 4, P. 59–78.
9. Pereira F.C. A Metamodel for estimating Error Bounds in Real-Time Traffic Prediction Systems / Pereira F.C., Antoniou C., Fargas J.A., Ben-Akiva M. // IEEE Transportation on Intelligent Transportation Systems. – 2014. – Vol. 15, Is. 3, P. 1310–1322. doi:10.1109/TITS.2014.2300103
10. Kļevecka I. Forecasting Network Traffic: A Comparison of Neural Networks and Linear Models / Kļevecka I. // Proceedings of the 9th International Conference Reliability and Statistics in Transportation and Communication (RSTC-2009), (21–24 October), Riga, Latvia, 2009. – P. 31–36.
11. Strelkovskaya, I.V. Spline approximation based restoration for self-similar traffic / Strelkovskaya I.V., Solovskaya I.N., Severin N.V., Paskalenko, S.A. // Eastern-European Journal of Enterprise Technologies. – 2017. – Vol. 3/4 (87), P. 45–50. doi:10.15587/1729-4061.2017.102999
12. Strelkovskaya I. Spline-Extrapolation Method in Traffic Forecasting in 5G Networks / Strelkovskaya I., Solovskaya I., Makoganiuk A. // Journal of Telecommunications and Information Technology. – 2019. – Vol. 3, P. 8-16. doi:10.26636/jtit.2019.134719
13. Strelkovskaya I.V. Using spline-extrapolation in the research of self-similar traffic characteristics / I. Strelkovskaya, I. Solovskaya // Journal of Electrical Engineering. Vol. 70 (2019), Is. 4, pp. 310-316. https://doi.org/10.2478/jee-2019–0061
14. Zavyalov Yu.S. Methods of spline functions / Zavyalov, Yu.S., Kvasov, B.I., Miroshnichenko, V.L. – M.: Science, 1980. – 288 s.

ЛІТЕРАТУРА:

1. 3rd Generation Partnership Project. "Study on Scenarios and Requirements for Next Generation Access Technologies", ETSI TR 38.913, V14.3.0, 2017. Access mode: https://www.etsi.org/deliver/etsi_tr/138900_138999/138913/14.02.0060/tr_138913v140200p.pdf
2. 3rd Generation Partnership Project. "Study on Architecture for Architecture for Next Generation System", TR 23.799 V14.0.0, 2016. Access mode: https://portal.3gpp.org/ desktopmodules/Specifications/ SpecificationDetails.aspx?specification Id=3045
3. Крылов В.В. Теория телетрафика и ее приложения / В.В. Крылов, С.С. Самохвалова. – СПб.: ВНХ-Петербург, 2005. – 288 с.
4. Sarigiannidis P. Predicting Multimedia Traffic in Wireless Networks: A Performance Evaluation of Cognitive Techniques / Sarigiannidis P., Aproikidis K., Louta M., Angelidis P. // Proceedings of the 5th International Conference on Information, Intelligence, Systems and Applications (IISA-2014), (7-9 July 2014), Chania, Greece, 2014. – P. 341-346. doi: 10.1109/IISA.2014.6878802
5. Kumar V. Short-term traffic flow prediction using seasonal ARIMA model with limited input data / Kumar V.,Vanajakshi L. // European Transport Research Review, Springer. – 2014. – Vol. 7-21, P. 9-21. doi: 10.1007/s12544-015-0170-8
6. Li C. A novel Self-Similar Traffic Prediction Method Based on Wavelet Transform for Satellite Internet / Li C., Han Y., Sun Z., Wang Z // EAI Endorsed Transactions on Ambient System. – 2017. – Vol. 4, Is. 14, P. 1–7. doi:10.4108/eai.28-8-2017.153306
7. Aldhyani Theyazn H. H. An Integrated Model for Prediction of Loading Packets in Network Traffic / Aldhyani Theyazn H. H., Manish R., Joshi / Proceedings of the Second International Conference on Information and Communication Technology for Competitive Strategies. (4-5 March), Udaipur: India, 2016. – P. 1–8. doi: 10.1145/2905055.2905236
8. Oravec M. Video Traffic Prediction Using Neural Networks / Oravec M., Petras M., Pilka P. // Acta Polytechnica Hungarica. – 2008. – Vol. 5, № 4, P. 59–78.
9. Pereira F.C. A Metamodel for estimating Error Bounds in Real-Time Traffic Prediction Systems / Pereira F.C., Antoniou C., Fargas J.A., Ben-Akiva M. // IEEE Transportation on Intelligent Transportation Systems. – 2014. – Vol. 15, Is. 3, P. 1310–1322. doi:10.1109/TITS.2014.2300103
10. Kļevecka I. Forecasting Network Traffic: A Comparison of Neural Networks and Linear Models / Kļevecka I. // Proceedings of the 9th International Conference Reliability and Statistics in Transportation and Communication (RSTC-2009), (21–24 October), Riga, Latvia, 2009. – P. 31–36.
11. Strelkovskaya, I.V. Spline approximation based restoration for self-similar traffic / Strelkovskaya I.V., Solovskaya I.N., Severin N.V., Paskalenko, S.A. // Eastern-European Journal of Enterprise Technologies. – 2017. – Vol. 3/4 (87), P. 45–50. doi:10.15587/1729-4061.2017.102999
12. Strelkovskaya I. Spline-Extrapolation Method in Traffic Forecasting in 5G Networks / Strelkovskaya I., Solovskaya I., Makoganiuk A. // Journal of Telecommunications and Information Technology. – 2019. – Vol. 3, P. 8-16. doi:10.26636/jtit.2019.134719

13. Strelkovskaya I.V. Using spline-extrapolation in the research of self-similar traffic characteristics / I. Strelkovskaya, I. Solovskaya // Journal of Electrical Engineering. Vol. 70 (2019), Is. 4, pp. 310-316. https://doi.org/10.2478/jee-2019–0061

14. Завьялов Ю.С. Методы сплайн-функций / Завьялов Ю.С., Квасов В.И., Мирошниченко В.Л. – М.: Наука, 1980. – 288 с.

DOI: 10.33243/2518-7139-2019-1-2-77-85