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HIGH-SPEED COMMUNICATION NETWORKS CHAOTIC BEHAVIOR ANALYSIS OF DATA SYSTEMS

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Chaos and self-similarity are the state-of-the-art problems in various areas of modern science and technology, thus network systems are not exception from this rule. Increasing number of various network protocols, applications and services leads to the fact that network traffic becomes more complex and unpredictable. It has been shown that phenomenon of self-similarity is caused by the properties of network traffic whose origin is the behavior of TCP protocol. And all this properties became more significant with appearing of the high-speed data transmission technologies. Finally this behavior leads to congestion in network and packet losses as the result of it. But even modern congestion control mechanisms handle such kind of situations quite unfair. For example, as shown by W. Feng et al., TCP Reno loss rate exceeds 5% in a heavily congested network. So it's easy to calculate that over a Gigabit Ethernet link such loss rate translates into a loss of over 50 Mb/s. Obviously this level of loss rate is unacceptable. However models that describe behavior of information systems sufficiently and give a possibility for scientists to apply all set of classical methods of chaos theory and analyze particular nonlinear dynamical system have not been offered so far. Phase portraits of the studied system were built and Lyapunov exponents for different values of the basic system parameters were calculated. In the present paper a new approach in analysis of the packet switching networks behavior with TCP protocol is proposed. These networks are analyzed as nonlinear dynamical systems that show chaotic properties at a certain value of parameters.
KEY WORDS: self-similarity, network traffic, chaos, packet loss, quality of service, TCP/IP

ВИВЧЕННЯ ХАОТИЧНОЇ ПОВЕДІНКИ ВИСОКОШВИДКІСНИХ МЕРЕЖ ЗВ'ЯЗКУ ІНФОРМАЦІЙНИХ СИСТЕМ

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Проблема самоподоби в різних областях науки та техніки цікавила дослідників давно. Поява та широке розповсюдження комп'ютерних мереж, а також зріст кількості різноманітних послуг привело до того, що мережевий трафік став більш складним і непередбачуваним. Особливо сильно ці властивості стали проявлятися з появою технологій високошвидкісної передачі даних. Це пов'язано з тим, що одним із основних показників якості (QoS) роботи мережі з пакетною передачею даних є кількість втрачених пакетів. Втрата пакетів призводить до додаткового навантаження на мережу і зрештою до «заторів». При великих швидкостях передачі даних втрата пакетів, що виражається в долях відсотка сприяє значним стратам інформації. В багаточисленних роботах, присвячених дослідженню мереженого трафіка було показано, що вказані вище явища пов'язані з властивостями самоподібного трафіка, основною причиною якого є поведінка протоколу TCP. Проте до сіх пір не були запропоновані моделі, які б адекватно описували поведінку систем зв'язку інформаційних систем, що дозволили б застосувати весь арсенал класичних методів аналізу нелінійних динамічних систем. В роботі пропонується новий підхід щодо аналізу поведінки мереж зв'яку інформаційних систем з протоколом TCP – розгляд їх як нелінійних динамічних систем, що проявляють хаотичні властивості за наявності визначених значень параметрів. Побудовані фазові портрети досліджуваної системи, розраховані показники Ляпунова для різних значень основних параметрів системи. Запропоновані рекомендації щодо проектування та експлуатації високошвидкісних оптичних мереж зв'язку інформаційних систем.
КЛЮЧОВІ СЛОВА: самоподоба, мережений трафік, хаос, втрата пакетів, якість обслуговування, TCP/IP

ИЗУЧЕНИЕ ХАОТИЧЕСКОГО ПОВЕДЕНИЯ ВЫСОКОСКОРОСТНЫХ СЕТЕЙ СВЯЗИ ИФОРМАЦИОННЫХ СИСТЕМ

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Проблема самоподобия в различных областях науки и техники интересовала исследователей давно. Появление и широкое распространение компьютерных сетей, а также увеличение количества разнообразных сетевых услуг привело к тому, что сетевой трафик стал более сложным и непредсказуемым. Особенно сильно эти свойства стали проявляться с появлением технологий высокоскоростной передачи данных. Это связано с тем, что одним из основных показателей качества (QoS) работы сетей с пакетной передачей является количество потерянных пакетов. Потеря пакетов приводит к дополнительной нагрузке на сеть и, в конечном счете, к «заторам». При больших скоростях передачи данных потери пакетов, выражающиеся в долях процента, приводят к значительным потерям информации. В многочисленных работах, посвященных исследованию сетевого трафика, было показано, что указанные выше явления связаны со свойствами самоподобия трафика, основной причиной которого является поведение протокола TCP. Однако до сих пор не были предложены модели, адекватно описывающие поведение систем связи информационных систем, позволяющие применить весь арсенал классических методов анализа нелинейных динамических систем. В работе предлагается новый подход к анализу поведения сетей связи

информационных систем с протоколом TCP – рассмотрение их как нелинейных динамических систем, проявляющих хаотические свойства при определенных значениях параметров. Построены фазовые портреты исследуемой системы, рассчитаны показатели Ляпунова для различных значений основных параметров системы. Предложены рекомендации по проектированию и эксплуатации высокоскоростных оптических сетей связи информационных систем.
КЛЮЧЕВЫЕ СЛОВА: самоподобие, сетевой трафик, хаос, потери пакетов, качество обслуживания, TCP/IP

For a long time the problem of self-similarity was interesting for researchers in different fields of science and engineering (hydrology, geophysics, biophysics, biology, financial economics) (an extensive enough bibliography is contained in [1]). Network traffic has become more complex and unpredictable because of appearance and wide propagation of computer networks and growth of different network services. Especially with appearance of high-speed data transmission technologies these qualities have shown up themselves strongly. It is connected with one of the major network work characteristics (QoS) with packet transmission is a number of lost packets. The loss of packets leads to additional load on any network and congestions in the final analysis. The high-speed data transmission loss of packets expressed in percentage leads to considerable loss of data. And even the bandwidth increasing of network affects on the improvement of its work poorly.

For the first time applying the conception of self-similarity for telecommunication systems was proposed by B. Malderbrot [2].

In the following numerous studies dedicated to the network traffic research has been shown all the above mentioned phenomena are connected with self-similarity traffic properties.

For the last 10-15 years a great amount of studies has been dedicated to the self-similarity network traffic problem. They can be divided into two large groups symbolically. The first group and the most extensive one includes the studies which the authors analyze the network traffic and define its statistic characteristics. The data analyzing source is either a full-scale experiment (for instance [3]) or modeling by means of application software (for instance ns [4], OPNET [5]).

To the second group related the studies (unfortunately they are not numerous) in which the data system is considered to be the dynamic one where self-similarity is an inner property of the system itself [6].

The goal of the given article is to consider the data communication networks with TCP protocol as non-linear dynamic systems which show some chaotic properties under certain parameter values and a new approach to behavior analysis of such systems is proposed.

THE CAUSES OF THE NETWORK TRAFFIC SELF-SIMILARITY

Most researchers believe that TCP is the main reason of traffic self-similarity (the basic transport Internet protocol). To understand the influence of TCP protocol on the network traffic self-similarity is to describe the TCP operation algorithm in general terms [7,8,9].

TCP is a service directed to the connection which ensures reliable (in accurate sequence) delivery of byte flow. Releasing applications from necessity “to worry” about missed or reordered data. It includes the control mechanism which ensures that a sender doesn’t overfill the recipient buffer and the congestion control mechanism tries to prevent the oversized data volume injection in network (which leads to the loss of packets). While the window size of the data flow control is static, the congestion window size is changing during long time in compliance with the network status. There are several modifications of the TCP protocol implementation (Reno, Vegas, Tahoe). Obviously, the most widespread is TCP Reno [10].

The TCP Reno congestion control mechanism is composed of two phases: (1) slow start and (2) congestion avoidance. At the slow start phase the congestion window size increases exponentially (i.e. it doubles every time when the sender transmits the amount of bytes successfully which is equal to the current congestion window size in network) until doesn’t emerge the timeout which means the loss of packets. At that moment the Threshold value is set in an amount of a half the window. TCP Reno restarts the congestion window size to one packet and returns at the slow start phase increasing the congestion window exponentially to the value of Threshold. When threshold reached TCP Reno enters the avoidance congestion phase in which the congestion window is increased by one packet each time as the sender transmits content of window successfully in network. When a packet is lost during the avoidance congestion phase TCP Reno attempts the same actions as when a packet is lost during slow start phase.

Here and now TCP Reno implements fast retransmit as well and it carries out the fast recovery mechanism for both the congestion avoidance phase and the slow start phase. If the sender receives three double ACK (an indication that some packet had been lost but subsequent packets were received) then the sender will retransmit a lost packet immediately (fast retransmit) instead of carrying out a timeout situation waiting acknowledgement (ACK) of the lost packet. Since subsequent packets were received the network congestion is considered to be less serious than if all packets were lost. And the sender just decreases its congestion window by half and returns at the avoidance congestion phase repeatedly evading the slow start phase again.

TCP Vegas introduces the new congestion control mechanism which tries to prevent them and it doesn’t react to appeared congestions. When the congestion window size increases then expected transmission rate (ER) increases as well. But if actual transmission rate (AR) remains the same it will mean that the available bandwidth is poor to provide transmission rate ER. Hence any extension of the congestion window size will result in overfilling the router buffer in the bottleneck gateway. TCP Vegas tries to detect this phenomenon and avoid congestion in the router bottleneck gateway adjusting the congestion window size and consequently ER adapting for the available bandwidth. TCP Vegas defines two threshold values α and β for the congestion avoidance phase to regulate the congestion window in a proper way. The third threshold value γ is defined for crossing between the congestion avoidance phase and the slow start phase. Conceptually, $\alpha = 1$ means that TCP Vegas tries to keep at least one packet from each flow located in a queue of the router while $\beta = 3$ keeps three packets maximum. In consideration of Diff = ER – AR Vegas increases the congestion window linearly during the next RTT (Round Trip Time) if Diff $< \alpha$. When Diff $> \beta$ then Vegas decreases the congestion window linearly during the next RTT otherwise the congestion window stays invariable. The parameter γ can be considered as "initial" value when TCP Vegas enters its congestion avoidance phase. To improve more TCP characteristics Floyd and the others proposed to use RED routers (Random Early Detection) [12] to detect incipient congestion. The RED routers support weighed mean lengths of a queue. While the weighed mean length of a queue stays below minimum threshold ($\min th$), all packets remain in a queue. When the weighed mean length of a queue exceeds ($\min th$) packets will be skipped (lost) with probability P. And when the weighed mean length of a queue exceeds maximum threshold ($\max th$), still arriving packets will be lost.

In recent years several new modifications of TCP protocol have been proposed. There are Binary Increase Control TCP (BIC-TCP), CUBIC TCP, Westwood TCP (TCPW), Parallel TCP Reno (P-TCP), Scalable TCP (S-TCP), Fast TCP, HighSpeed TCP(HS-TCP), HighSpeed TCP Low Priority (HSTCP-LP), Hamilton TCP (H-TCP), Yet Another Highspeed TCP(YeAH-TCP), Africa TCP, Compound TCP etc.

Almost all of them are based on well-known old TCP versions and they differ from each other various congestion avoidance means. To be more precise they are based on different ways of detecting the packets loss occurrence fact which means appearance of congestion. Various formulas for cwnd (congestion window) calculation are used in different modifications.

ESSENCE AND RELEVANCE OF THE PROBLEM

To study congestions arising in computer networks and avoidance methods is the very topical question at modern stage of the computer network development. New technologies such as GRID and distributed calculations are appearing and they transmit quite great amount of data via network. Videoconferences and applications for transferring voice represent more and more tough quality of service (QoS) requirements. The Internet network is developing and at the same time an amount of users is increasing as well. Hence growth of the transfer traffic capacity which compounds about 7500-1200 PBytes per month at the end of 2009. All these factors are precondition for appearing congestions in computer networks.

Well studied and tested methods of the theory of chances are suitable for describing and preventing network congestions. Also the Internet architecture of protocols places certain limitations. For example competitive TCP flows and all plurality of transport protocols used in computer networks don't know anything about each other but various models of the congestion control in TCP and other protocols should coexist in harmony. If one of implementations turns out to be more aggressive than the others then it will use a major part of the bandwidth which can prevent from the data transmission in "adjacent" connections. At the same time unnecessary conservatism of an algorithm will have a negative impact on the general protocol performance.

THE TEST BED

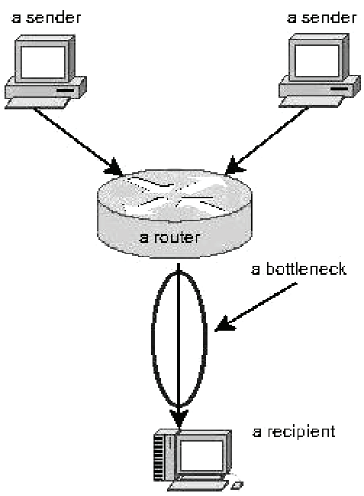


Fig. 1. The model network topology

It has been used the discretely temporal simulator with source code NS-3 (Network Simulator 3) in the present work for investigating TCP flows. NS-3 gives a researcher the class set which can be used and modified. Thus it is possible to simulate the wide range of protocols and processes occurring in computer networks. Also the simulator makes possible to model processes in real time and integrate it with the test bed making this a part of modeling network etc. The NS-3 simulator includes the great amount of tests for all components which guarantees veracity obtained results. The model of TCP/IP network has been created by means of the given simulator where all hosts connected with a router by the point-to-point connection type (Fig. 1). The work of the application has been simulated in sender hosts sending data with permanent bitrate to the host recipient where the application worked and received data from the both type of hosts. The data generation rate of senders (C_f), the delay (d_b) and the bandwidth of pipes in the bottleneck and also the delay and the bandwidth of pipes in host senders were varied specifying particular parameters for each numerical experiment. The type Drop Tail Queue (Q_s) queue size also was varied in the router network interface connected with the recipient.

The receiving host window (rwnd) was made very large deliberately to make limiting factor the only value of the congestion window (cwnd).

Obviously in such network the congestion state will be occurred when total rate sending data from the sender host exceeds the bandwidth of the recipient channel. Therewith the key parameters affecting on congestion appearance are C_f, d_b, C_b, and Q_s because sender hosts have sufficient bandwidth and low delay and it won't affect on the congestion control algorithm by TCP protocol. There will be shown the values only these parameters in the further description of numerical experiments.

THE BEHAVIOR STUDYING METHODOLOGY OF TCP PROTOCOL

The variables number characterizing state of the given system is very large even in such simple system with two TCP connections. But it can be chosen a suitable section of the phase space by force of proper selection these variables. The magnitude of congestion window has been chosen because it affects on the data transmission rate directly.

It was tracking an alteration of each TCP flow cwnd values from the sender to the recipient during the work simulation process of two TCP-connections. A new value and a time moment were recorded into the file for each cnwd value variation when this alteration happened. Finally two time sequences specifying the step-type function which contains cwnd dependence of time have been obtained for two hosts (as cwnd value is stored in memory all the time and it changes at fixed time moments).

But there is not enough cwnd dependence of time for studying given process in details. The problem lies in the fact that the congestion window value is just a projection of the full set of system variables. Therewith the cwnd(t) function is not continuous. The second problem is that the congestion window value doesn't make possible to draw a conclusion about system status in details starting from the certain time moment.

In this work it has been proposed to use averaging over N values of the time sequence $\left[x_t, x_{t-\sigma\cdot t}, x_{t-2\sigma\cdot t}, \ldots\right]$ as easy measured characteristic of complex systems and showed that it can be used for recovery of the hidden multidimentional trajectories. The given method applied to the congestion window values (cwnd) leads to the relations [6]:

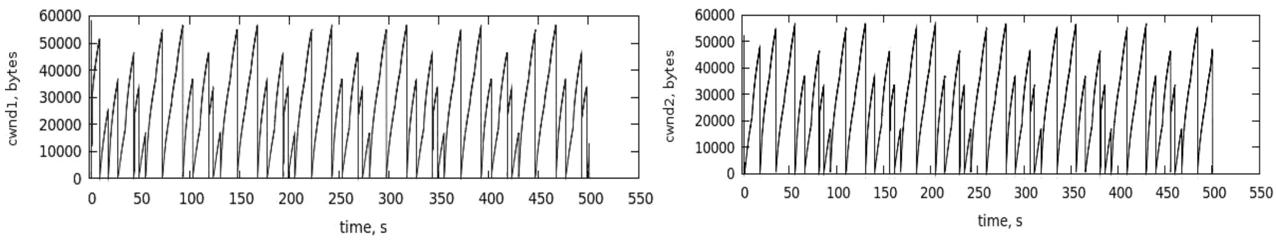
$$x[i] = \frac{1}{N}\sum_{j=1}^{N} cwnd_x[i-j],$$
$$y[i] = \frac{1}{N}\sum_{j=1}^{N} cwnd_y[i-j]. \qquad (1)$$

Two TCP flows are indicated as x and y here. The N quantity is responsible for a scale of averaging and the more N the more hidden dimensions of the system can be recovered.

In this case cwnd(t) functions are different for hosts and only moments of changing values this function are fixed. Therefore to apply mentioned above method and to plot a phase portrait means to get the congestion window values at the same moments of time.

THE PHASE PORTRAIT

Such system seems to be easy enough and it shows quite difficult behaviour under certain parameters of the test bed. Specifically the graphics of cwnd(t) dependence if C_f =5Mbps, d_b=10ms, C_b=5Mbps, Q_s=20 packets[1] and more hard mode under Q_s=2 packets are mentioned below. Regular beating can be noticed in the both plots. And each TCP flow takes an advantage one over another by turns at the particular time intervals.

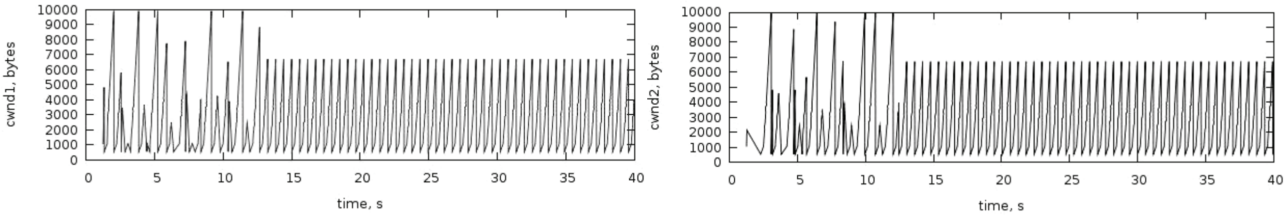


a) b)

Fig. 2. The congestion window dependence of time
a) the first TCP-flow under C_f =5Mbps, d_b=10ms, C_b=5Mbps, Q_s=20,
b) the second TCP-flow under C_f =5Mbps, d_b=10ms, C_b=5Mbps, Q_s=20

According to described algorithm in the previous section the associating phase portraits are obtained by data processing and displayed respectively in the Fig. 2-3. In case of N=2000 and d_t=10 ms the phase portraits are shown in the Fig. 4-5.

[1] 1 packet = 536 bytes, in all conducted numerical experiments



a) b)

Fig. 3. The congestion window dependence of time
a) the first TCP-flow under C_f =5Mbps, d_b=10ms, C_b=5Mbps, Q_s=2
b) the second TCP-flow under C_f =5Mbps, d_b=10ms, C_b=5Mbps, Q_s=2

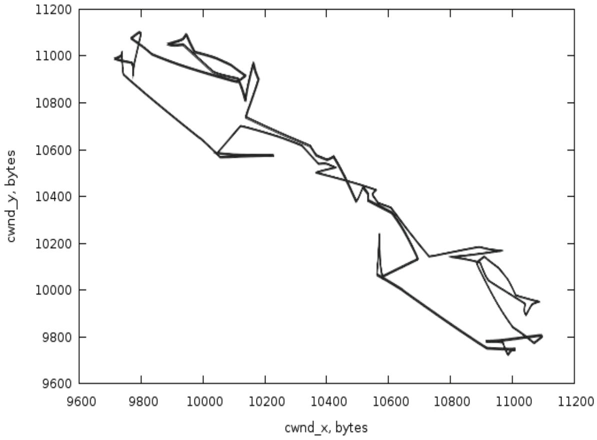


Fig. 4. The phase portrait
under C_f =5Mbps, d_b=10ms, C_b=5Mbps, Q_s=20
(the regime initialization transient process was removed)

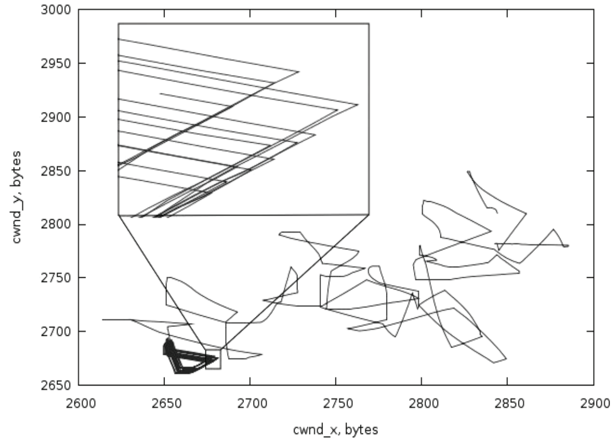


Fig. 5. The phase portrait
under C_f =5Mbps, d_b=10ms, C_b=5Mbps, Q_s=2
The cycle section was scaled up to make possible to see its complex structure.

As can be seen the phase trajectories shape the limit cycle which has a quite delicate structure. And this trajectory is pretty steady because an image point after little "roaming" begins to describe the same closed trajectory in process of TCP flows start time changing relatively one another. For comparison data and the phase portrait are stated below when senders don't overfill the recipient pipe. In other words there is no congestion (Fig. 6 and Fig. 7). In this case the cwnd value of both hosts increases indefinitely as expected and there is no any anomalies in the phase portrait.

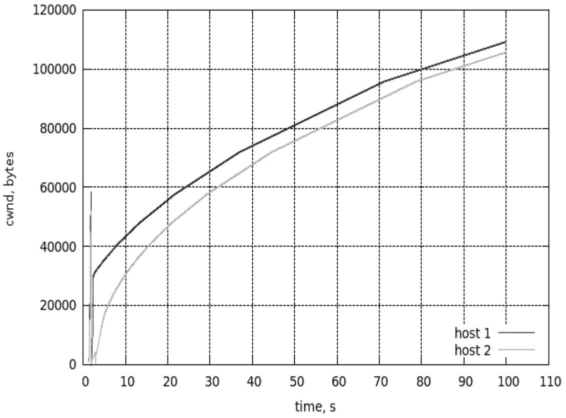


Fig. 6. The congestion window dependence of time
under C_f =2Mbps, d_b=10ms, C_b=5Mbps, Q_s=100 (there is no congestion)

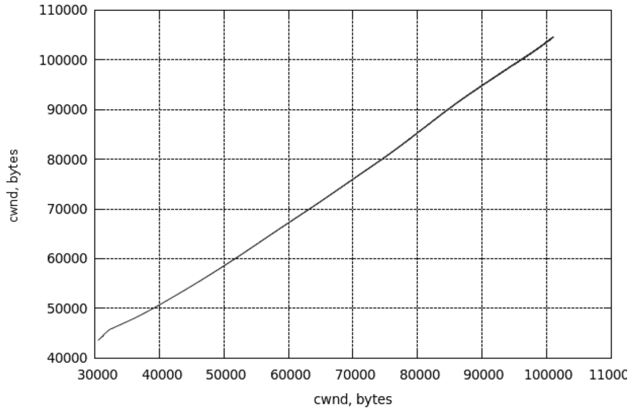


Fig. 7. The phase portrait
under C_f =2Mbps, d_b=10ms, C_b=5Mbps, Q_s=100

THE MAXIMUM LYAPUNOV EXPONENT

Phase portraits are useful not only to show the dynamic system status. If you have a phase portrait you will be able to calculate a maximum Lyapunov [2] exponent λ. It's the quantity which is able to characterize the recession rate of close trajectories and usually its positive value is considered to be an indicator of the system chaotic behaviour.

However to graph the system phase portrait is possible only in a few cases. When one adds a new sender into the simulated network then the analyzed phase space dimensionality will increase by one and to analyze obtained data will

[2] For example using Benettin's algorithm [15]

be more complicated. Apart from the phase space visualization is possible if its dimensionality is fewer than 4.

Thus it is necessary to have the instrument which allows obtained data to be tested aside from a number of available TCP sessions. For this purpose the utility package TISEAN has been chosen [16]. It is intended for analysis of time series and based on the theory of nonlinear deterministic dynamic systems or the chaos theory. TISEAN is represented to be an implementation of the theory chaos algorithms. However these algorithms don't give "simple" answers to questions taking into account the research field newness where hasty utilization of algorithms can bring to incorrect, unclear or false results. Therefore for instance asking the question about attractor dimensionality it can't be given the finite numerical answer. Instead of this it will be computed the correlated sum which can be analyzed by other utility package. A researcher is responsible for correct interpretation of work results.

The utility lyap_k from TISEAN package has been used for calculating the maximum Lyapunov exponent. The result of its work is the data set which represents the logarithm coefficient of trajectories recession dependence of time $S(\varepsilon, m, \Delta n)$ [17], it is computed in the following way:

$$S(\varepsilon, m, \Delta n) = \frac{1}{N} \sum_{n_0=1}^{N} \ln \left(\frac{1}{\left|U(s_{n_0})\right|} \times \sum_{s_n \subset U(s_{n_0})} \left(s_{n_0+\Delta n} - s_{n+\Delta n} \right(\right), \quad (2)$$

where ε is neighbourhood of S_{n_0} point, m is dimensionality of the phase space, Δn is time, and $U(S_{n_0})$ – neighbourhood of the point S_{n_0} with diameter ε.

In the given algorithm the point S_{n_0} is chosen in the phase space and its "neighbours" remote from S_{n_0} within ε distance are marked. Then average distance to all the "neighbours" is calculated as a function of passed Δn time. Thus at the time moment $n_0 + \Delta n$ (plus a logarithm of the initial state) a logarithm of average distance is some effective rapidity of trajectories recession during Δn time. All fluctuations have been averaged out under repetition described steps for quite large amount n_0 values. If $S(\varepsilon, m, \Delta n)$ quantity shows linear increase with the same slope in the reasonable range of ε values then slope ratio approximating this part of the line can be considered to be roughly equal to the maximum Lyapunov exponent.

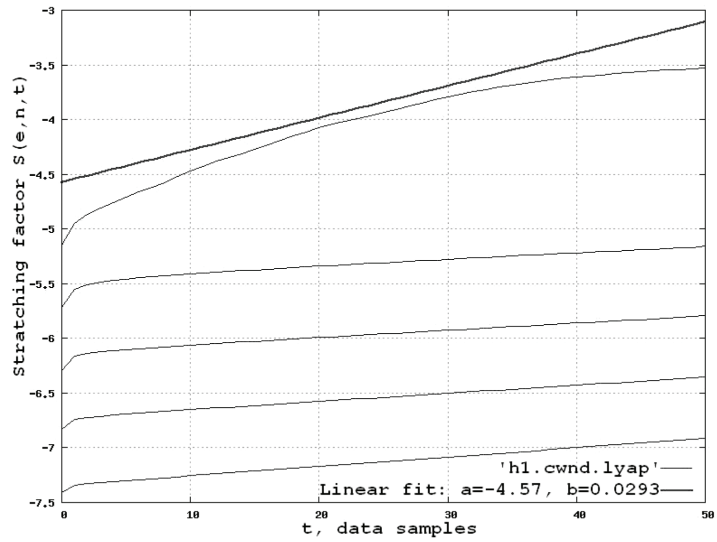


Fig. 8. The Lyapunov exponent calculation
(Q_s=20: λ ~ 0.029)

The results obtained after processing and visualization cwnd(t) time series are represented here and they have been brought into accordance with Fig. 4,5 and 7 (take a look at Fig. 8 − 10) with the aid of lyap_k utility. The curves $S(\varepsilon, m, \Delta n)$ for five different ε values and the line $y = a + bx$ approximating linear section of these curves are pictured in the figures. Thus b value equals to the maximum Lyapunov exponent numerically.

The data obtained in process of the network work simulation in the absence of congestion have been analyzed. In this case as expected if λ < 0 such system doesn't show chaotic behaviour proceeding from experiment definition as can be seen in the graph.

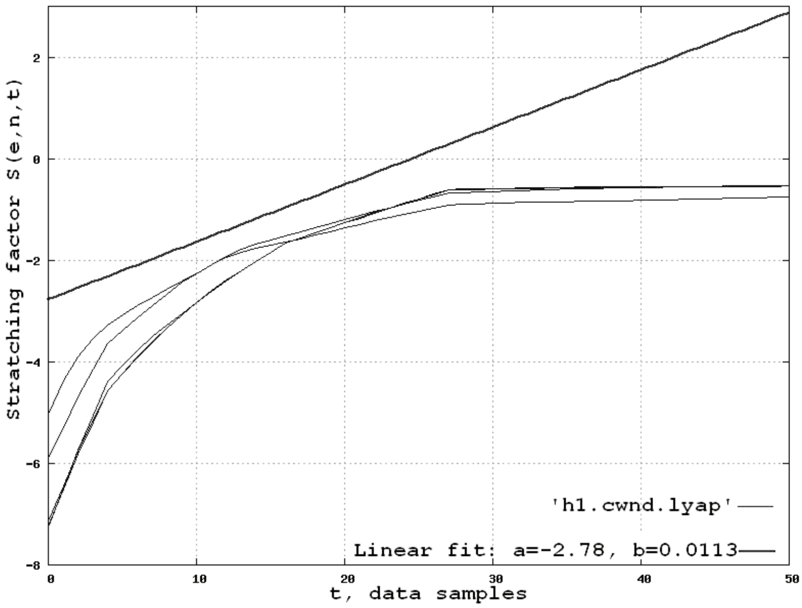


Fig. 9. The Lyapunov exponent calculation
(Q_s=2: λ ~ 0.113)

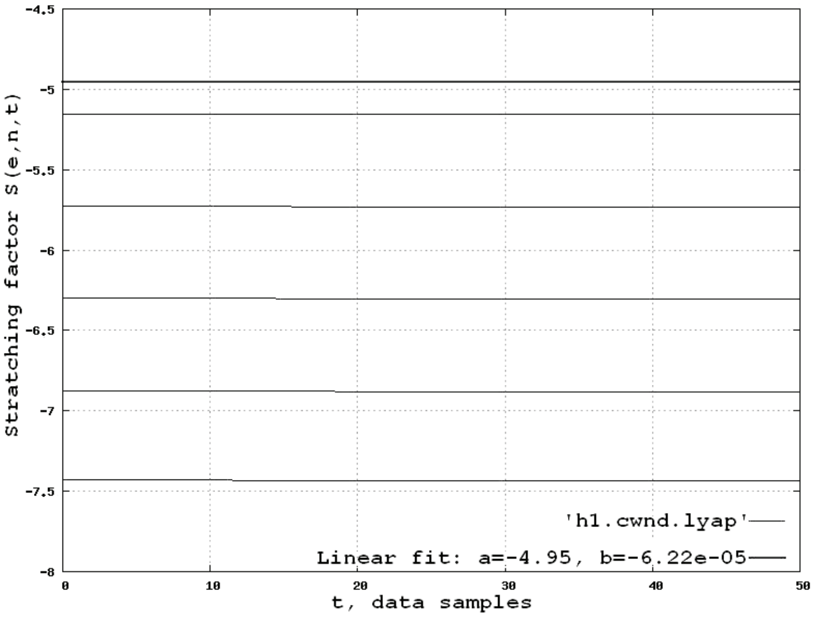


Fig. 10. The Lyapunov exponent calculation
C_f =2Mbps, d_b=10ms, C_b=5Mbps, Q_s=100:
λ ~ -0.00006 means absence of chaos

THE CONCLUSIONS AND FURTHER RESEARCH DIRECTIONS

The carried out research makes possible to conclude that the router buffer size is one of the key parameters influencing on TCP protocol work.

According to our reckoning the further way consists of describing communication networks of data systems using the TCP protocol as nonlinear dynamic systems. In this case there is a possibility to apply all the classical methods set of behavior analysis such systems developed by Poincare, Lyapunov, Birkhoff. It concerns with qualitative analysis of the dynamic system behavior in the phase space which gives an opportunity to define all possible system motion (work) modes and to detect parameter values that cause undesirable chaotic phenomena (the loss of packets, performance decreasing) In the first place these questions are topical for the ISP (Internet providers) who unfortunately don't pay proper attention to them. Obviously to solve the problem of congestions and the loss of packets is not possible on a global scale the whole of Internet network in connection with inability to redesign the whole network in virtue of technical and economical reasons.

However it is possible to give some recommendations to design (and further exploitation) for the limited in scale networks (even large enough) that allows negative phenomena of chaotization to be minimized.

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