Scholars Journal of Engineering and Technology (SJET) **ISSN 2321-435X (Online)**
Sch. J. Eng. Tech., 2014; 2(3B):395-402 **ISSN 2347-9523 (Print)**
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www.saspublisher.com

Research Article

Design of Information and Telecommunication Systems with Multi-Hour, Multiservice Traffic and Multilayer Graph Usage

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Abstract: At the current moment, despite the large number of publications in the direction of self-similar traffic studies, deficit of studies involving the use of models for the synthesis of multi-service telecommunication networks. In this regard, this article solves the problem of parametric synthesis of multiservice transport network where aggregated traffic is transmitted from a large number of users. Based on the analysis of publications was selected: model of aggregated traffic in the form of fractional Brownian motion; formulas for determining the parameters of multicast traffic, which resulting in aggregation of multiple flows; formulas for delay and the packet loss probability and proposed methods for the parametrical synthesis of telecommunication networks with the use of these models and formulas. Considered in the paper is the overlaid nature of modern telecommunication networks and expediency of usage the multi-layer graph model for its design. General statement of design problem is given. The design method in general using multi-layer graph model with multi-hour flows and its application for a typical information and telecommunication system is proposed.
Keywords: multilayer graph; overlay network; information and telecommunication system; design; multi-hour traffic

INTRODUCTION

Nowadays, when the number of users of networking applications increases enormously, the management of network resources is a hot-topic issue. On the other hand, as technology develops, the capacities of network devices become larger and larger; a few years ago 155 Mbps links were general but now 10 Gbps links are also available. However, the need for bandwidth increases more rapidly than capacities of routers and links, since the bandwidth requirements of novel networking applications are higher and higher. Further, sometimes it is not worth extending the existing networks since the old technology that does not support novel applications or the extension is restricted by physical limitations. For these reasons the establishment of new networks using new technologies is essential. Thus, Internet service providers (ISPs) can make use of an algorithm that can solve the problem of network design aiming at reducing the deployment cost.

An important issue considering the profitability of ISPs is how economically they can utilize their resources. In order to reach the optimal network performance, administrators should have full control over traffic flows. A possible approach of capacity management is multi-hour design (MHD) [1]. Multi-hour design—as opposed to single-hour design (SHD), which results in a network that is dimensioned for maximal (busy hour) traffic demands—takes the periodic change of traffic volumes and directions into account by partitioning the whole time scale into several intervals and calculating the maximal traffic demands separately for each interval. As the maximal demand between different node pairs may occur in different intervals, the capacities of network devices may be smaller than in the case of single-hour design, resulting in lower deployment cost. This design approach takes the ability of reconfiguration into account already at the network design phase.

Modern telecommunication systems are constructed on the basis of overlay networks (i.e. each lower level of the network provides transparent transfer of the network flow over the upper level); thus, they have a multi-layer structure formed with topology hierarchy. When solving design problems, it is necessary to determine the network structure on each layer.

Known approaches for solving design problems use the step-by-step synthesis separately for each level to consider the multi level nature of systems. Synthesis results of one level are the source data for the rest of the levels. In this case the interconnections and interdependences between the levels are not considered. As the result, the final configuration is not optimal.

To solve this problem, the authors propose [2, 3] to use the multi-layer network model represented as an ordered set of graphs. Topology of each graph can be different; they may have different sets of edges; in this case, as a rule, the set of upper layer nodes is a subset of the lower layer nodes.

The above model of the multi-layer network structure has an accurate correspondence of nodes in graphs that describe each layer. At the same time, a lot of systems have interlevel connections of a more complex nature, for which the above model is no longer adequate. To eliminate this drawback, the model based on multi-layer graph is proposed [4, 5, 6].

To date, telecommunication network capacity design based on the use of teletraffic theory methods. Mathematical models that make up this theory well describe the processes occurring in such systems as the telephone network, built according to the principle of switching channels. The most common call flow model of teletraffic theory is a stationary Poisson flow.

At the same time, as shown by research results, information flows have completely different structure. This leads to the fact that the calculation of the parameters of the telecommunications network designed for the maintenance of such traffic by classical formula gives incorrect and unreasonably optimistic results. A more adequate model for describing these flows are models of self-similar (fractal) processes that take into account as defined hereinbefore properties of information flows.

At the current moment, despite the large number of publications in the direction of self-similar traffic studies, deficit of studies involving the use of models for the synthesis of multi-service telecommunication networks. In this regard, this article solves the problem of capacity design of multiservice network where aggregated traffic is transmitted from a large number of users. Based on the analysis of publications was selected: model of aggregated traffic in the form of fractional Brownian motion; formulas for determining the parameters of group traffic, which resulting in aggregation of multiple flows; formulas for delay and the packet loss probability and proposed methods for the capacity design of multiservice networks with the use of these models and formulas.

METHODOLOGY

Modeling of information and telecommunication system with multi-layer graph

Graphs are widely used for the mathematical modeling of the structure of systems including telecommunication systems. When the system is described using a graph, the system elements are modeled as nodes, and connections between them are modeled as arcs or edges.

For overlay networks modeling [4], we propose to use multi-layer graph $MLG = (\Gamma, V, E)$, which includes:

- a set of subgraphs $\Gamma = \{\Gamma^1, \ldots \Gamma^l, \ldots, \Gamma^L\}$, where the subgraph $\Gamma^l = (V^l, E^l)$ describes the network structure on the layer l;

- nodes $v_i \in V$ and edges $e_k = (v_i, v_j), \quad e_k \in E$ provide the interconnection between subgraphs Γ^l.

The structure of graph MLG modeling telecommunication networks is subject to an additional constraint which reads that for each edge $e_k^l = (v_i^l, v_j^l)$, $e_k^l \in E^l$ of subgraph Γ^l there exists a path $\pi = (v_i^l, \ldots, v_m^n, \ldots v_j^l)$ between the nodes v_i^l and v_i^l, $v_i^l, v_j^l \in V^l$, that passes through the lower layer graph:

$$\forall e_k^l = (v_i^l, v_j^l), \quad e_k^l \in E^l, \quad v_i^l, v_j^l \in V^l, \ \exists \pi = (v_i^l, \ldots, v_m^n, \ldots, v_j^l), v_m^n \in V^n, n < l. \qquad (1)$$

This rule does not apply only for the lowest layer subgraph, $l = 1$.

Describing telecommunication networks with the multi-layer graph allows considering technological hierarchy of modern networks, specifically, overlaid principle of their construction in contrast to classic graphs.

The description of telecommunication system with multi-layer graph is done in accordance with the following strategy [6].

Step 1. Distinguish the set of layers in the modeled telecommunication system.

Step 2. Describe the topology of each layer with a classic graph.

Step 3. Distinguish logical, functional and physical connections between the objects on the different layers and describe them with graphs.
Step 4. Assign the edges and nodes a set of parameters, describing the parameters of the respective objects and connections that are of interest for modeling.

On step 1 we distinguish a set of overlay structures in the modeled system. They can act as a separate object for analysis.

On step 2 we define the network topology for each separate layer distinguished on step 1. For this:
- every node of the network on this level is represented as a graph node.
- pairs of directly interconnected nodes are determined (i.e. pairs of nodes that do not use other nodes of this layer as transit nodes to interconnect between each other).
- for each pair of the directly interacting nodes, we include an edge into the graph that connects the corresponding graph vertices.

On step 3, each edge included into the multi-layer graph corresponds to the logical and physical connection between the nodes of the overlay networks.

On step 4, each edge of the multi-layer graph is ascribed a number of parameters corresponding to the parameters of the network being modeled.

Self-similar traffic modeling and calculation

For solving problems of telecommunication network capacity design is necessary to choose a model for group traffic which formed by combining traffic coming from multiple sources. The results of the research group for modeling flow with the effect of self-similarity is well-suited model based on the use of fractional Brownian motion [7]. This model proposed Leland et al [8] used Norros [9, 10] for expressions describing the quality of service characteristics of a group of self-similar flow in the network nodes .

Group traffic in a telecommunications network channels (fractional Brownian traffic) is represented as

$$\xi(t) = \lambda t + \sqrt{\varsigma\lambda} B_H(t), \qquad (2)$$

where $\xi(t)$ is interpreted as the amount of data received during time interval $(0, t]$. This traffic model has been considered and analyzed in many works [8, 11, 12] and others for various technologies packet-switched networks and for various telecommunication services.

Fractional Brownian traffic model has three parameters $\{\lambda, \varsigma, H\}$ that describe the flow characteristics such as the average rate λ (packets per sec or bits per sec), which is a quantitative characteristic of the traffic, as well as parameters ς (package·s or bits·s) and dimensionless H, which describes the qualitative characteristics of the traffic. Parameter ς is the variance coefficient

$$\varsigma = \sigma^2 / \lambda. \qquad (3)$$

This parameter characterizes the degree of fluctuations in flow relative to its average value. Using the parameter ς instead variance is convenient because when change the flow rate λ, which can be considered as a change in the aggregate amount of homogeneous flows, allows you to change the parameter λ, while leaving unchanged the other two parameters.

Used in the expression (2) the process $B_H(t)$ - is the normalized fractional Brownian motion with zero mathematical expectation $M[B_H(t)] = 0, \forall t$ and variance $D[B_H(t)] = |t|^{2H}, \forall t$. Note that $B_H(t)$ is a mathematical object that has no physical dimension, and its argument t - also dimensionless. Therefore, when modeling information flows better to use $B_H(t/t_u)$, where t - physical time, and t_u - the time unit. When $H = 1/2$ the fractal Brownian motion degenerates into a classical Brownian motion and the process $\xi(t)$, if $\varsigma = 1$ coincides with the diffusion process, known from the classical theory of teletraffic.

In solving problems of telecommunication network capacity design is necessary to determine the parameters of aggregated traffic, when combined in a network node several self-similar flows. Based on the work in [13] can be concluded that the aggregation of the two streams, of which at least one has the property of self-similarity, the resulting stream is self-similar too. Process $\xi(t)=\xi'(t)+\xi''(t)$, obtained as the superposition of two processes, $\xi'(t)$ and $\xi''(t)$ can be written:

$$H=\mathbf{max}(H_1,H_2). \quad (4)$$

Applying for the case of aggregation of more than two flows $\xi(t)=\sum_i \xi_i(t), i=1,\ldots,N, N>2$ pairwise aggregation operation

$$\xi(t)=(\cdots(\cdots(\xi_1(t)+\xi_2(t))+\ldots+\xi_i)\cdots+\xi_N), \quad (5)$$

obtain the following expression:

$$H=\mathbf{max}_i(H_i),\ i=1,\ldots,N. \quad (6)$$

Equation (6) can be used to estimate value of the parameter Hurst for aggregated flow. For other parameters aggregated flows, such as rate λ and coefficient of variance ς, the following expressions:

$$\lambda=\sum_i \lambda_i, \quad (7)$$

$$\varsigma=\frac{\sum_i \varsigma_i\lambda_i}{\sum_i \lambda_i}. \quad (8)$$

Using the model described fractal Brownian motion, Norros obtain expressions relating the probability of losses, the required channel capacity, average queue length, buffer size [9, 10, 14]. Based on the results obtained Norros can write the following expressions for the packet delay τ in the node and the probability of packet loss P due to buffer overflow [15, 16] when the input traffic to the effect of self-similarity:

$$\tau=\frac{\iota}{c}\left[1+\frac{\lambda^{2H-1/2(1-H)}\cdot c^{1/2(1-H)}}{(c-\lambda)^{H/1-H}}\right], \quad (9)$$

$$P=\mathbf{exp}\left[\frac{(c-\lambda)^{2H}}{2k(H)^2\varsigma\lambda}\ell^{2-2H}\right], \quad (10)$$

where ι - the average length of the packet;

$k(H)=H^H(1-H)^{1-H}$;

ℓ - buffer size.

Problem statement

Telecommunications network, which synthesized, transmits traffic between network nodes $a_i \in A$, which are sources of aggregated traffic, and included transit nodes $z_i \in Z$.

Given:

$A=\{a_i\}$ - set of network nodes - sources of information flows;

$S=\{s_k\}$ - set of services provided by the network;

$\gamma_{ij}^k(t)$ - traffic parameters between node pairs sender-receiver when providing services in a time interval (busy hour) *t*;

- is known, network topology and routes of transmission traffic between all pairs of nodes sender-receiver;

α_{ij} - the unit costs for the communication channel (a_i,a_j) bandwidth.

Necessary to determine the capacity of communication channels c_{ij} so that the average delay in the network does not exceed a predetermined value T_{det}. Criterion of optimality minimum total cost of building a network.

Problem solution

According to the general method of solving the problem of synthesizing a telecommunications network with the use of multilayer graph [6] in the structure of the synthesized network shall allocate the following levels (layers).

Bottom layer is multilayer graph MLG graph describing the physical network topology. Vertices of the graph correspond to the physical network nodes, and edges - the communication channels of the physical network.

Layers above the bottom describe the interaction nodes infocommunication systems in service delivery. The number of layers is equal to the number of services. Vertices v_i^l correspond to the sources of information flows and consumers of services. Edges e_{ij}^l connect vertices that correspond to the network nodes cooperating in the provision of services.

We assign the to each edge of the graph Γ^1 parameter $\alpha_c(e_{ij}^1, c_{ij}) = \alpha_{ij} c_{ij}$ specifies the costs of organizing the communication channel bandwidth c_{ij}.

We assign the to each edge e_{ij}^l of the flow $\gamma_{ij}^l(t) \in \Upsilon^l$. The above flows are aggregated flows occurring in the time interval *t* and their describing fractional Brownian traffic model, characterized by a set of parameters: $\lambda_{ij}^l(t)$ - flow rate, bit/s; $\iota_{ij}^l(t)$ - average packet length, bit; $\varsigma_{ij}^l(t)$ - the coefficient of dispersion; $H_{ij}^l(t)$ - Hurst parameter.

Vertices of the graphs Γ^l, $l = 2, \ldots, L$ a re connected by edges $e_{ij}^{l,1} = (v_i^l, v_j^l)$ to the vertices of the lower layer, which correspond to nodes a_j in the network, where the source of information flow or consumer services.

Multilayer structure of the graph for an example of two services in a network is presented in Fig-1.

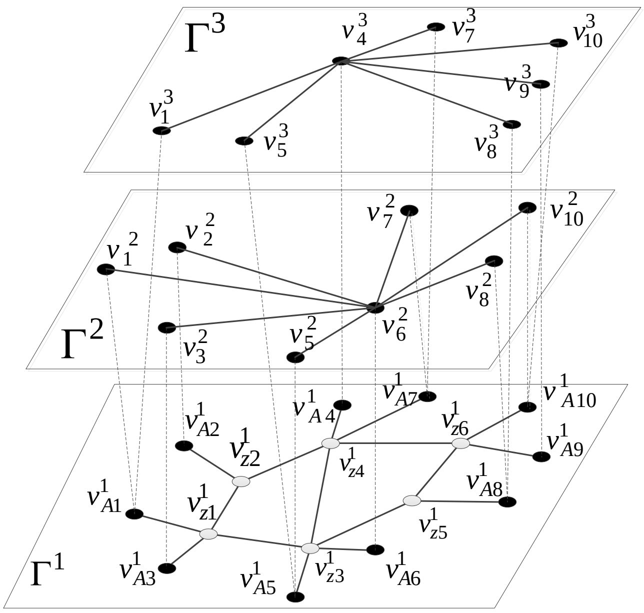

Fig-1: Multilayer graph structure

Denote $\gamma_{ij}^1(t)$ as stream flowing along the edge of the graph of the lower layer. Stream γ_{ij}^1 is formed by combining streams corresponding stream flowing along the edges of the upper layers of the multilayer graph [17]:

$$\gamma_{ij}^{1}(t) = \sum_{\substack{l=2,\dots,L,\\ e_{km}^{l}\in E^{l},\, e_{ij}^{1}\in\pi_{(km)}^{1}}} \gamma_{km}^{l}(t), \quad \forall i, j, t. \qquad (11)$$

Parameters of aggregated streams flowing along the edges of the graph Γ^1 can be determined according to the procedure described previously. On this basis, we can write

$$\lambda_{ij}^{1}(t) = \sum_{\substack{l=2,\dots,L,\\ e_{km}^{l}\in E^{l},\, e_{ij}^{1}\in\pi_{(km)^l}^{1}}} \lambda_{km}^{l}(t), \qquad (12)$$

$$\iota_{ij}^{1}(t) = \sum_{\substack{l=2,\dots,L,\\ e_{km}^{l}\in E^{l},\, e_{ij}^{1}\in\pi_{(km)^l}^{1}}} \left(\iota_{km}^{l}\lambda_{km}^{l}(t)\right) \Bigg/ \left[\sum_{\substack{l=2,\dots,L,\\ e_{km}^{l}\in E^{l},\, e_{ij}^{1}\in\pi_{(km)^l}^{1}}} \lambda_{km}^{l}(t)\right], \qquad (13)$$

$$\varsigma_{ij}^{1}(t) = \sum_{\substack{l=2,\dots,L,\\ e_{km}^{l}\in E^{l},\, e_{ij}^{1}\in\pi_{(km)^l}^{1}}} \left(\varsigma_{km}^{l}(t)\lambda_{km}^{l}(t)\right) \Bigg/ \left[\sum_{\substack{l=2,\dots,L,\\ e_{km}^{l}\in E^{l},\, e_{ij}^{1}\in\pi_{(km)^l}^{1}}} \lambda_{km}^{l}(t)\right], \qquad (14)$$

$$H_{ij}^{1}(t) = \max_{\substack{l=2,\dots,L,\\ e_{km}^{l}\in E^{l},\, e_{ij}^{1}\in\pi_{(km)^l}^{1}}} \left[H_{km}^{l}(t)\right]. \qquad (15)$$

In this case srednesetevuyu delay, using the expressions (9) according Little formula can be defined as

$$\overline{T}\left(\Gamma^{1}, \Upsilon(t), c\left(e^{1}\right)\right) = \frac{1}{\Lambda(t)} \sum_{e_{ij}^{1}\in E^{1}} \left[\frac{\lambda_{ij}^{1}(t)}{c_{ij}^{1}} \left(1 + \frac{\left(\lambda_{ij}^{1}(t)\right)^{\left(2H_{ij}^{1}(t)-1\right)/\left(2-2H_{ij}^{1}(t)\right)} \cdot c^{1/\left(2-2H_{ij}^{1}(t)\right)}}{\left(c_{ij}^{1} - \lambda_{ij}^{1}(t)\right)^{H_{ij}^{1}(t)/\left(1-H_{ij}^{1}(t)\right)}}\right)\right],$$

$$\Upsilon(t) = \left\{\Upsilon^{l}(t)\right\}, \qquad (16)$$

$$\Lambda(t) = \sum_{l=2,\dots,L} \sum_{\substack{\gamma_{km}^{l},\\ e_{km}^{l}\in E^{l}}} \lambda_{km}^{l}(t) \Big/ \iota_{km}^{l}. \qquad (17)$$

Thus, based on the mathematical model of infocommunication system, formulate the problem of capacity design as an optimization problem of the following form.

Given: $MLG = (\{\Gamma^{l}\}, E, \alpha(e^{1}))$ - multilayer graph that describes the structure infocommunication systems;
$\Upsilon(t) = \{\Upsilon^{l}(t)\}$ - set of flows flowing along the edges of multilayer graph *MLG* during the time interval *t*.

Necessary to find: $c_{ij}^{1}, \forall e_{ij}^{1} \in E^{1}$ - capacities of edges in the corresponding communication channels synthesized telecommunications network.

Criterion of optimality:

$$\Psi = \sum_{e_{ij}^{1}\in E^{1}} \alpha_{ij} c_{ij}^{1} \to \min. \qquad (18)$$

Constraints:

$$\overline{T}(\Gamma^{1}, \Upsilon(t), c(e^{1})) \le T_{\partial on}, \quad \forall t, \qquad (19)$$

$$\gamma_{ij}^{1}(t) = \sum_{\substack{l=2,\dots,L,\\ e_{km}^{l}\in E^{l},\, e_{ij}^{1}\in\pi_{(km)}^{1}}} \gamma_{km}^{l}(t), \quad \forall e_{ij}^{1} \in E^{1}, \forall t \qquad (20)$$

$$\lambda_{ij}^{1}(t) < c_{ij}^{1}, \quad \forall e_{ij}^{1} \in E^{1}, \forall t, \qquad (21)$$

The problem of parametric synthesis (18) - (21) was reduced to a problem without constraints and solved using the method quickest gradient descent.

The method described solutions implemented as software code and analyzed on a PC. Research methodology was based on the following.

For each variant of the flow coming into network, an assessment values of its parameters within the Poisson (flow rate and average packet length) and a self-similar model (flow rate, the average packet length and Hurst parameter). Subsequently with the use of the obtained values of flows produced bandwidth selection of communication channels.

As a result of experiments conducted it was established that the method has a higher efficiency than earlier known, are based on simplest flow models.

CONCLUSION

The analysis results of this work showed that the synthesized mathematical model of infocommunication enterprise network as a multilayer graph can improve the efficiency of solving problems of synthesis and describe the system as a single coherent entity.

The proposed method can more accurately determine the capacity of communication channels in which the average delay in practice most closely reflects the magnitude expected to solve the problem of parametric synthesis;

As a result of the experiment, it was confirmed that the use of methods based on the Poisson model gives too low flow requirements for network resources, which leads to configurations having higher value average delay and consequently having a worse quality of service parameters.

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