Examination of congestion phenomena in computer networks using the methods of the statistical physics

József Stéger

Eötvös Loránd University
Faculty of Science
PhD School of Physics

Head of PhD School: Zalán Horváth, DSc, Full member of HAS
Supervisor: Gábor Vattay, DSc, professor

Department of Physics of Complex Systems

Main results

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Introduction

The system we study in our work is a complex system. We investigate the behaviours of computer networks and also their manifestation at a higher level, the Internet, which influence our everyday life widely. Applications operating in the Internet help us doing our daily work, they have become an essential part of our life, thus they have a significant impact both on our individual and social habits. It is of utmost importance to know the characteristics and the limits of the network in detail, in order to maintain reliable and efficient operation of their applications.

Internet is a continuously evolving system of different autonomous computer networks, which are interconnected without a central management. The large number of components communicating with each other are self-organising. Both the characteristics of the network topology and the numerous interesting phenomena describing the information traffic have drawn the attention of natural scientists. It has been shown by various experiments, that the structure of the Internet wears the signs of scale-free systems. For instance the number of the neighbouring building components falls according to power law. Also Internet is well described by the small world phenomenon, ie. despite the fact that the system constitutes of approximately 10^8 nodes, its diameter is well smaller than 100. Former experiments highlight, that in the spectrum of the traffic in the network $1/f$-noise is present. Often the amount of the information transmitted in unit time over a given link shows self-similarity, ie. averaging the quantity over different time intervals, the deviations and fluctuations will not fade away. By the help of different simulation environments chaotic behaviour of the network traffic has been shown for the proper combination of the parameters. Understanding and modelling these phenomena are challenging tasks for physicists, as well. Well founded and proper models help in dimensioning the network and in organising traffic efficiently.

Information is transported by packets in the network. The dynamics of the individual traffic flows are ruled by well-defined equations of motion. On their way from the sources to the destinations information packets meet at different nodes in the network, where they share the available resources. Packets share free serving capacity, and they stand in queues if necessary. The queueing process of the packets lead to congestion in the network. Packet belonging to different streams interact, which introduce difficult couplings in the motion equations. Stochastic phenomena and the probabilistic quantities in the equations start playing an important role.

The dynamics of the packet flows generated by the applications „talking" to each other in the network are ruled by many factors. One of the most important of these quantities is the network delay suffered by individual packets. It also accounts for the potentials of the network for a given time. Naturally the drastic increase in the network delays lead to the degradation of the efficiency of information transfer. Extreme delays deriving from queueing lead to congestion, which of course worsen the conditions of the communication, thus it is important to minimise their probability of occurrence. Today the task of sidestepping congested network nodes is an unsolved open problem. The goal of our research is to create an accurate picture of these delays describing computer communication networks, and to reveal the possible places of congestion.

During my work, in a fruitful cooperation with my colleagues, in order to investigate and to understand network traffic better, I took both theoretical and experimental steps, which are described in the theses. The theses work consists of 5 main chapters. In chapter *Fogalmak* (Terms) a historical overview of the computer networks is given and the most important terms are introduced, which are necessary for the understanding of the discussion. We planned and built a measurement system, which made it feasible to conduct all of the experiments that compose an important part of our research, and which enabled us to construct the map of the European Internet's traffic. This is detailed in *A mérőhálózat* (The measurement platform) chapter. Archiving and publishing the data gathered by various network measurements are important tasks, which inspire science to move forward. The infrastructure, which serves evaluation methods and their results besides the raw measurement data, is shortly described in chapter *Hálózatmérési virtuális obszervatórium* (The network measurement virtual observatory). One of the most important type of measurements our research group is delivering is the network tomography. Network tomography infers the statistical properties of the internal network. In chapter *A hálózati pufferek sorhosszainak becslése tomográfiás módszerekkel* (Estimating the delays of network queues using tomography techniques) the methods of statistical physics is detailed, which evaluate the raw data of our tomography experiments. According to the results of our experiments network traffic shows signs of fractal features. We discover a new scaling law of queueing delays. In chapter *Torlódási hullám modellje* (The model of congestion waves) a theoretical model is developed, which catches the evolution of the spatio-temporal patterns of congestion.

This model is in good accordance with the results of the network simulators.

Main results

1. The main goal of our experimental research is to make the spatial and temporal course of the network load visible. To achieve this we use the mathematical techniques of the Bayesean methods, which are known to be practical in the statistical physics to reveal the unmeasurable quantities of a system. We elaborate the formulae and the algorithms of estimators used in the tomography for Y and tree topologies. By the help of these estimators the queueing delay distributions are revealed, and it is possible to reconstruct the traffic map for the European Internet. The flavour of the active measurements we use is that we do not have a direct access to the internal nodes, the internal details are merely revealed by these tomography techniques.[1, 2, 3, 4]

2. According to the results of the network tomography we introduced, the queueing delay distributions vary on a wide range, the values of the average and the variance span over 3 orders of magnitude. Queueing delay distributions belong to the Weibull function class according to the relation between their first two moments. Resulting distributions can be classified in 3 groups: 1) the details of the segments building the fast core of the network are not resolvable, 2) the distributions of compound segments resemble after the distributions of network delays over the whole path, 3) one-queue segments are described by falling density functions, from which the Hurst parameter describing the fractal properties of the background traffic is derivable. [4]

3. Besides the inspections of individual queueing delay distributions, we looked at their collective properties for each different experiments. The counter cumulative distribution of the queueing delay averages in most cases fall according to the $1/x$ power law. This scaling feature of the Internet is a new discovery and which we relate to the serving capacities present at the different nodes of the network. It is also interesting to note the fact that points of the CCDF follow a continuous function despite the discrete possible capacities of network building blocks. [4]

4. To fulfil tomography measurements it is indispensable to construct, de-

velop and operate a precise measurement system. An important part of our work was to create the European Traffic Observatory Measurement Infrastructure (ETOMIC), which was done in an international collaboration. When planning the tomography measurement applications we investigated the possible ways to enlarge the size of the network that can be measured by adding external cooperative systems or programmes. It is also part of our work to build the observatory prototype, in which the huge amount of measurement data, including the tomography data are published. [5, 6, 7, 8] With the help of the observatory analysis of data extending over the individual measurements is possible, for instance we can assign an estimate to the stability of a network path by the mere analysis of delay data between the endpoints.

5. In computer systems the motion equations of traffic regulation are well known and deeply studied. By virtue of the models of analogous systems of transport networks, like the highway models or the models for the flow of granular matters in pipelines, we rightly expect collective phenomenon to build up. In our model a simple ring topology was studied. We show how congestion builds up and propagate. The phenomenon is similar to those found in the highway models, where the stop-and-go like speed regulation introduces congestion. We provide a formula for the speed of the congestion wave, which is travelling against the packet flow. In this model we determine the parameters describing the envelope of the congestion wave, and we study stability of the different possible parameter sets, foretold by the theory. [9]

Publications

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