Fractal Based Network Traffic Model and its Applications: A Survey

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Abstract: Today, the Internet is growing exponentially, with traffic statistics that mathematically exhibit fractal characteristics: self-similarity and long-range dependence. With these properties, data traffic shows high peak-to-average bandwidth ratios and causes data networks inefficient. These problems make it difficult to predict, quantify, and control data traffic, in contrast to the traditional Poisson-distributed traffic in telephone networks. Traffic on packet switched networks, such as the Internet, has been shown to exhibit characteristics that are very different from traditional telephone network traffic. In particular, it is busy on multiple time scales, shows long-range rather than short-range dependence in its autocorrelation, and is statistically self-similar, i.e., fractal. These characteristics impact network performance in adverse ways and complicate network design. In this research a new view of self-similar traffic structure is proposed. This view is an improvement over the theory used in most current literature, which assumes that the traffic self-similarity is solely based on the heavy-tailed file-size distribution. Their statistics differ from Poisson processes. An important finding is that the relationship between the bandwidth and the transfer delay is nonlinear. The self-similar or multi fractal traffic can be simulated when the parameters are different in certain ranges.

INTRODUCTION

There was only one kind of traffic of any significance, and that was voice. It had (and has) well-known characteristics, namely Poisson interarrival rates and exponential call length distribution. There was no need to worry about things such as network layers, as they did not exist. It was easy to measure critical values of the important parameters. Queueing theory permitted design of voice networks to meet any desired performance characteristics.

With packet networks, multilayer protocols are here to stay. This means many more invariants, as one or more are generally associated with each network layer, far more complicated traffic statistics, and, accordingly, much greater difficulty analyzing and simulating network traffic. There are also a far greater number of applications (not just voice conversation), each with its own traffic characteristics, and new applications can arise at any time. There are many more varieties of network connectivity, architecture, and equipment, and, accordingly, different types of traffic flow. There are no Similar behavior over these scales — suggests that fractals are the most appropriate mathematical tool to describe certain aspects of network behavior. The problems of packet network design are summarized.

The Network Design Problem

The design of circuit-switched networks, used for over 100 years to carry telephone traffic throughout the world, is a well-understood and highly refined discipline. Such networks can be engineered to provide any desired level of service. This is because the underlying voice traffic characteristics, first investigated by Erlang in 1909-1918, [5] are also well-understood and have been the basis of elaborate theoretical development. Such networks are highly static in their topology. Growth rates are very predictable, and network controls are highly or fully centralized, which means that information about the network’s global state can be utilized for system optimization. And, finally, all services are highly regulated and monitored. standard network topologies around which all design efforts can be based, and the topologies that exist are subject to constant change. “Success disasters” occur regularly: new software technologies which spread like wildfire through the Internet before they can be optimally engineered. And perhaps most serious and most surprising, packet networks (unlike voice networks) exhibit burstiness on multiple time scales. Such burstiness observed over a wide range of time scales — which means The vast rise of the Internet and other packet-switched data networks has led to a type of crisis in network design, because the packet traffic carried over these networks has entirely different characteristics than voice traffic. Two problems arise as a consequence: (1) when traditional telephone networks are utilized for data traffic, such
as fax and dial-up Internet access, significant performance degradation can occur, to the extent that call blocking can reach unacceptable proportions; and (2) design techniques and methods developed for voice networks do not yield satisfactory results when the attempt is made to apply them to data network design. Although problem (1) may be alleviated over the next few years as more users switch to cable modems and Digital Subscriber Loop (xDSL) technology, problem (2) will only be solved with better understanding of packet network behavior. This implies that new network Design principles must be developed for packet switched data networks. The problem of burstiness can be readily understood from Figure 2, which shows the effect of looking at telephone traffic, which has Poisson arrival rates, with Internet traffic, which does not. As shown in Figure 2, packets per unit time are counted (vertical scale), for a given time interval (horizontal scale). The time interval is then increased by a factor of 10 (for the second and third graphs) and by a factor of 7 (for the last or bottom graphs). The unit time interval is increased by this same factor. Traffic here is measured at the link layer. In effect, the averaging intervals become longer from top to bottom.

As the figure shows, averaging Poisson or voice traffic over longer intervals reduces burstiness, whereas Internet traffic shows the same burstiness regardless of time scale. This means that traffic peaks in voice networks are limited in frequency of occurrence and severity, and a voice network can be engineered to reduce ill effects below any desired threshold. The similar appearance of the graphs on the right-hand side of Figure 2, regardless of time scale, is the telltale sign of fractal behavior.

Figure 2. Burstiness In Poisson Or Ordinary Telephone Traffic (Left) and Internet Or Packet Network Traffic (Right), Measured at the Link Layer; Burstiness “Averages Out” For Telephone Traffic, But Not Internet Traffic

Figure 3. Overview of Packet Network Traffic Tutorial

Goals of Network Analysis and Design

What is the goal of network analysis and design? The steps to reach that goal are summarized in Figure 4. For packet networks such as the Internet, considerable progress has been made on the first step, the search for invariants. The second step is especially important, because parsimonious models are those which are mathematically tractable and which can be applied over a wide range of conditions with considerable confidence and limited need to guess parameter values. [1]. In particular, most of the tools developed for telephone networks do not work for packet Networks. As an example, queuing
theory, a highly refined discipline often used to analyze networks, requires “well-behaved” probability distribution functions for its solutions to converge. Packet traffic is unfortunately characterized by ill-behaved distributions with “heavy-tails,” discussed below.

The Search for Invariants

As indicated above, the first step in all modeling, simulation, and analysis is to look for invariants, defined as some facet of Internet behavior shown to hold over a wide range of environments and to be observable by any observer. Such invariants are the “hooks” on which hang mathematical analyses of networks. Two of them have been used in voice telephony for 70 years, with great success:

Poisson arrival rates

Exponential call duration

Great heterogeneity of topology and applications

Constantly changing and non-standard topologies

New applications arising, e.g., World Wide Web

Changes within applications, e.g., shift from text to graphics to audio to video The net result is many invariants, each of which occurs at a specific layer, which enormously complicates the design problem. Network models must account for all invariants, and use them in the modeling and design process. Some of the principle invariants discovered to date in packet traffic are summarize in Table 1.

Internet Time Scales

The phenomena associated with Internet (packet) traffic emerge on different measurement time scales. Measurements indicate that Internet traffic characteristics vary by measurement time, but that there are three principal divisions, as shown in Figure 5. First, at extremely short time scales, up to a few hundred milliseconds, protocol effects — principally Transmission Control Protocol (TCP) — dominates. Current research suggests that this traffic may be characterized as a special type of fractal, called a multifractal. [9,10] On longer time scales, covering approximately four orders of magnitude, the traffic exhibits mono fractal or self-similar behavior, which accounts for its burstiness on these scales.

Basic Characterization of Data Networks

Data networks exhibit high or extreme variability. Indeed, there is a famous description of burstiness in packet traffic: traffic “spikes” ride on longer term “ripples,” traffic “ripples” ride on longer term “swells,” ad infinitum. Figure 3 showed that burstiness is the result of phenomena at several levels or protocol layers, which interact to produce it. Roughly speaking, the distribution of file sizes (an application layer statistic) affects transmission time statistics, which, in turn, shows up as self-similarity at the transport and network layers, and gives rise to long-range dependence, finally leading to burstiness seen at the link layer. So the character-istics of Internet traffic of interest are:[3]

Long-range dependence (LRD)

Self-similarity

Infinite variance
Heavy-tailed probability distribution functions

Burstiness

A complete treatment of these characteristics and the many techniques for measuring them is far beyond the scope of this brief tutorial, but for some, a brief description of each is given; readers may pursue the subject through the references given in the notes.

Long-range dependence. This refers to the degree of dependence of samples taken at one time on those of an earlier time. It is gauged quantitatively by the autocorrelation function. Autocorrelation of a stationary process measures the degree of correlation of nearby and far-off events, i.e., the ability

Heavy-tailed distribution and infinite variance.

The size of files sent over the Internet has been determined to have what is
to predict (in a statistical sense) process values removed in time from any given time.

Self-similarity. Network traffic has empirically been observed to be self-similar in a statistical sense, over a wide range of time scales. Objects with this self-similar quality are called fractals. Fractals are mathematical objects which exhibit self-similarity at multiple scales. They can exist in space, time, or a combination of the two. And the self-similarity can be with respect to shape, or statistical. It implies that the object consider-ed, if suitably scaled (magnified), will look like itself on a different scale.[3]

Evidence for Fractal Behavior In Internet Traffic

Network traffic has been extensively investigated since the discovery of burstiness and self-similarity in ethernet traces at Bellcore in the late 1980s. Traffic at various levels in the protocol It has been discovered that LAN and WAN traffic differ in significant ways, which affect traffic characteristic-

LAN time, completely transforming traffic characteristics at multiple layers, as shown in Figure 10.


