Available online at www.sciencedirect.com

SCIENCE DIRECT®

Computer Communications 29 (2005) 1–23

computer communications

www.elsevier.com/locate/comcom

Stochastic processes for computer network traffic modeling

Ian W.C. Lee, Abraham O. Fapojuwo*

Department of Electrical and Computer Engineering, University of Calgary, 2500 University Drive N.W., Calgary, Alta., Canada T2N 1N4

Received 2 July 2004; revised 31 January 2005; accepted 11 February 2005
Available online 14 March 2005

Abstract

Computer networks such as local area and wide area networks possess complex characteristics due to the heterogeneous nature of the supported traffic. The network traffic exhibits highly irregular fractal-like structure and long term correlations. Various stochastic processes such as fractional Gaussian noise, multiplicative cascades, linear fractional stable motion have been proposed to model network traffic. These stochastic processes are relatively unheard of in the networking community, until recently. This paper provides a thorough review of these stochastic processes and their application to wireless traffic modeling.

Keywords: Self-similarity; Long-range dependence; Fractals; Multifractals; Fractional stable motion; 1/*f* process; Point process; Infinitely divisible cascade; Traffic modeling

1. Introduction

Modeling of computer network traffic is an imperative first step towards the formulation of effective algorithms that manage the limited resources in the network. The difficulty in finding an accurate yet parsimonious model is due to the heterogeneous and complex nature of traffic running through the network. This problem is exacerbated by the fact that network traffic at one location may adversely affect traffic at other locations. Furthermore, computer networks are closed loop systems. For example, the network adapts to a change in demand for bandwidth, congested links, outages and transmission errors.

Typically two different time series are considered in traffic modeling. They are the traffic rate process and the packet inter-arrival times. Examples of traffic rate process are the number of packets per time unit or number of bytes per time unit. These time series can be extracted from various layers of the open system interconnection (OSI) protocol stack. However, the transport layer has been the most popular. Of this, the transmission control protocol (TCP) traffic has been the most researched. The traffic models that will be described in this paper are suitable for time series describing traffic rate process and packet inter-arrival times.

Traditionally, packet arrivals are modeled as a Poisson process. The reason for this is two-fold: its mathematical tractability that lends itself to amenable performance analysis and its excellent fit to circuit-switched networks. Furthermore, high quality computer network traffic traces were not readily available for analysis. Hence, the Poisson model was extrapolated to include packet-switched networks. One of the first studies on packet-based network traffic was performed by Leland et al. [1]. Leland et al. discovered that Ethernet traffic is bursty and correlated over a wide range of time scales. That is, Ethernet traffic is both self-similar and long-range dependent. These two important characteristics are not captured by parsimonious Poisson or Markov based models. However, they are naturally modeled in the framework of self-similar or fractal processes. Since the seminal work of Leland et al., many other researchers have reported that these characteristics are also present in other types of networks such as wide area network (WAN) [2], variable bit rate video [3] and wireless traffic [4]. The impact of long-range dependence on resource dimensioning was studied in [5,6]. Another significant discovery was made in [7–9] where it was found that the characteristics of

* Corresponding author. Tel.: +1 403 220 8524; fax: +1 403 282 6855.
E-mail addresses: iwclee@ucalgary.ca (I.W.C. Lee), fapojuwo@ucalgary.ca (A.O. Fapojuwo).

0140-3664/$ - see front matter
doi:10.1016/j.comcom.2005.02.004

WAN and asynchronous transfer mode (ATM) traffic at small time scales were very different and much more complex than those at large time scales where self-similarity dominates. They posit that network traffic at small time scales are multifractal.

Generally, traffic models can be categorized into two classes: black box models and structural models [10]. Black box models or classical time series models typically provide a good fit to observed time series but unfortunately are not intuitive or amenable to understanding of the dynamics governing the time series. Usually such models have certain parameters that can be adjusted to fit the time series. These parameters are then used for analytical work on performance measures of the network such as queuing behavior. Examples of black box models are fractional Brownian motion [11], fractional autoregressive integrated moving average (FARIMA) [12], and linear fractional stable motion [13]. In structural modeling, the objective is to reproduce the observed features of the measurements, using models whose parameters are related to the traffic generating mechanism and the behavior of the main components of the network [10]. Examples are the ON/OFF [1] and $M/G/\infty$ [2] models. The cost of moving from black box to structural models is loss in accuracy of fitted structural models to the empirical traffic trace. The focus of this paper is on black box models. A good review on structural models can be found in [14].

The goals of this paper are two-fold. First, we provide a comprehensive review of current state of the art stochastic processes that have recently been used to model computer network traffic. This paper serves as a complete and accessible reference on pertinent stochastic models catered to network engineers and researchers alike. The framework presented here allows us to show the relationships between different stochastic processes. The authors' acknowledge the existence of other review papers such as [15,16], whose main focus was on older Markovian based models. This paper is very pertinent as we review fractal, multifractal and alpha stable processes, which have superseded Markovian models both in terms of accuracy and relevance. The second goal of this paper is to demonstrate the applicability of these stochastic processes to wireless traffic modeling. Previous work has mainly focused on wired traffic [1,2,8,9]. However, the growing ubiquity of wireless networks in recent years necessitates research in wireless traffic. The paper is organized as follows: in Section 2 the classical Poisson model is presented. Fractal processes and their numerous manifestations are presented in Section 3. In Section 4, we touch on multifractal analysis and the two multifractal processes, the binomial cascade and infinitely divisible cascades. In Section 5, alpha stable distributions and linear fractional stable noise are reviewed. Section 6 presents the application of previously discussed stochastic processes to wireless traffic modeling. Conclusion and future outlook are presented in Section 7.

2. Poisson process

The Poisson process is a very popular model with a long history in the field of telecommunications. The success of the Poisson model in modeling voice traffic over circuit-switched networks is unquestionable. The strength of the Poisson model lies in its mathematical tractability. This is the reason why it is still used extensively today although its appropriateness in certain cases is questionable.

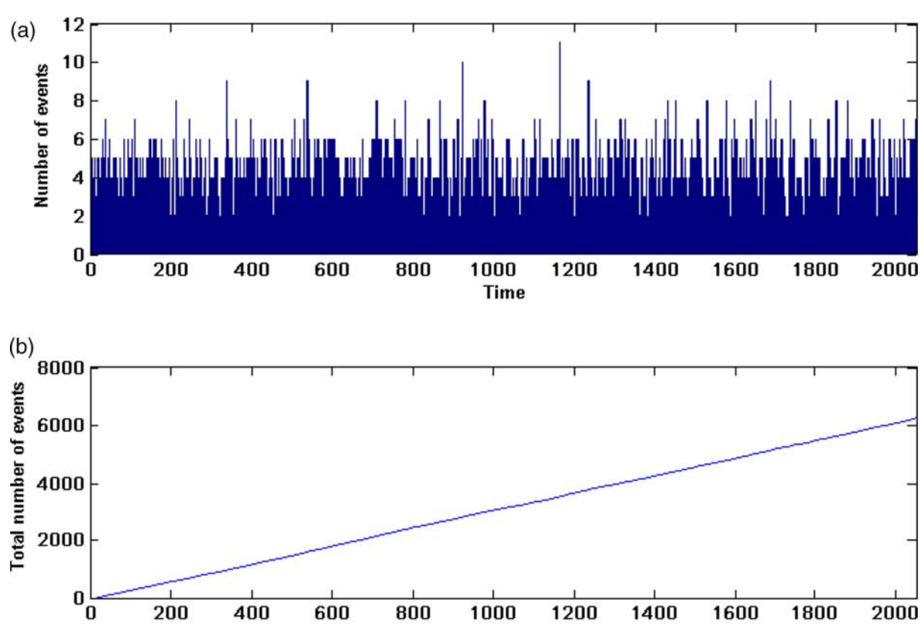

Fig. 1. (a) Rate process (increments); (b) Poisson process (counting process).