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Modeling network traffic using generalized Cauchy process

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Abstract

Processes with long-range dependence (LRD) have gained wide applications in many fields of science and technologies ranging from hydrology to network traffic. Two key properties of such processes are LRD that is characterized by the Hurst parameter H and self-similarity (SS) that is measured by the fractal dimension D. However, in the popular traffic model using fractional Gaussian noise (fGn), these two parameters are linearly related. This may be regarded as a limitation of fGn in traffic modeling from the point of view of either accurately fitting real traffic or appropriately explaining the particular multi-fractal phenomena of traffic. In this paper, we discuss recent results in traffic modeling from a view of the generalized Cauchy (GC) process. The GC process is indexed by two parameters D and H. The parameter D in the GC model is independent of H. Hence, it provides a more flexible way to describe the multi-fractal phenomena of traffic in addition to accurately modeling traffic for both short-term lags and long-term ones.

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Keywords: Long-range dependence; Hurst parameter; Fractal dimension; Self-similarity; Generalized Cauchy process; Network traffic; Time series

1. Introduction

Traffic models play a key role in computer communication networks (Adas [1]). In the field of computer science, people are seeking traffic models that are expected to be such that they are accurate and able to describe the statistical properties of the real traffic. Network systems are queuing systems. Due to the fact that the autocovariance function (ACF) and LRD of traffic have considerable impact on queuing systems (see e.g. Livny et al. [2], Tsybakov and Georganas [3], Hajek and He [4], Erramilli et al. [5], Li [6], Rolls et al. [7], Nain [8], Carpio [9]), the focus of this paper is on traffic's correlation models with LRD.

In the seventies of the last century, Tobagi et al. [10] reported a noticeable behavior of traffic, which is called "burstiness" defined by peak-to-average transmission rate [11, p. 45]. It simply implies that there would be no packets transmitted for a while, then a flurry of transmission, no transmission for another long time, and so on if one observes traffic over a long period of time. This also means that traffic has intermittency. In 1986, Jain and Routhier [12]

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further described the intermittency or burstiness of traffic using the term "packet trains". One of the significant results discussed in Ref. [12] is that traffic is neither a Poisson process nor a compound Poisson one, signaling a prelude of traffic modeling to be studied from the view of fractal time series.

The early work regarding the traffic properties described from the point of view of fractal time series, such as SS, LRD, $1/f$ noise, and heavy-tailed distribution,[1] was experimentally studied by Leland et al. [13], Beran et al. [14], Csabai [15], Paxson and Floyd [16]. A typical model of traffic therein is fGn introduced by Mandelbrot and van Ness [17]. Nevertheless, fGn has its limitation in traffic modeling. Paxson and Floyd [16, Last sentence, Paragraph 4, Section 7.4] remarked that "it might be difficult to characterize the correlations over the entire trace with a single Hurst parameter". In addition, Tsybakov and Georganas [18, Paragraph 1, Section II] noticed that "the class of exactly self-similar processes (i.e., fGn) is too narrow for modeling actual network traffic". In spite of this, fGn has been a widely used model of traffic till recently, see e.g. Abry et al. [19], Karagiannis et al. [20, Eq. (3)], Gong et al. [21], Lee et al. [22, Eq. (8)], He et al. [23], Stoev et al. [24].

We now consider two important properties of traffic, namely the local irregularity and LRD. The former is often termed burstiness in computer science. It is a local property of traffic, characterized by its fractal dimension D. The latter is a global property measured by the Hurst parameter $H \in (0, 1)$. Based on a single parameter model, such as fGn, D and H are linearly related by $D = 2 - H$, the derivation of which will be exhibited in the following section. Hence, a single parameter model fails to *separately* capture the local irregularity and LRD.

Experimental processing of traffic carried over wide-area networks (WANs) reveals that WAN traffic (traffic for short again) is robust at large time scales (beyond a few hundreds of milliseconds) but it has highly local irregularity (or large burstiness) at small time scaling (a few hundreds of milliseconds and below), see e.g. Paxson and Floyd [16], Feldmann et al. [25], Willinger et al. [26]. From a physical perspective, it is desirable to have two parameters, one for local irregularities and the other for LRD, to separately describe such scaling behavior of traffic. Models characterized by a single parameter model can be used to investigate variations of one parameter H or D, see e.g. Refs. [25–29], but they fail to provide separate observations of the variations of D and H.

Naturally, a premise to separately study the local irregularity and LRD of traffic is that the model should be indexed by two parameters. In the field of traffic modeling, several kinds of models indexed by more than one parameter have been reported. For instance, Karasaridis & Hatzinakos [30] and Gallardo et al. [31] utilized α-stable self-similar processes, where α is characteristic exponent of the α-stable distribution. However, under the constraint of LRD condition, α is related to H by $\alpha H > 1$. Hence, this kind of model is inappropriate for the purpose of separately describing the local irregularity and LRD. Therefore, in order to achieve the goal of separately characterizing the local irregularity and LRD, the two parameters indexing the model must be independent of each other. Recently, Gneiting and Schlather [32] introduced a model indexed by two parameters which provides separate characterization of fractal dimension and LRD. The Gaussian process used in the model was later called the generalized Cauchy (GC) process by Lim and Li [33]. We use this term in this paper.

The paper is organized as follows. In Section 2, we discuss briefly the two parameters H and D, and how they are related in the fGn model. Section 3 outlines the basic properties of the GC process. In Section 4, we study the traffic modeling based on the GC process. Section 5 gives a method of generating the GC process. Finally, Section 6 concludes the paper.

2. Fractal dimension of fGn linearly relates to its Hurst parameter

Let $X(t)$ be a stationary Gaussian process with zero mean for $-\infty < t < \infty$. Let $R(\tau) = E[X(t)X(t+\tau)]$ be the ACF of $X(t)$, where τ denotes the time lag. Then, if $R(\tau)$ is non-integrable, $X(t)$ is of LRD and it is of short-range dependence (SRD) otherwise. For the power-law type ACF that has the asymptotic property given by

$$R(\tau) \sim c\tau^{-\beta} \quad (\tau \to \infty), \tag{1}$$

where $c > 0$ is a constant, one has the LRD condition $0 < \beta < 1$ [34]. The parameter β is the index of LRD. Expressing β by the Hurst parameter H of fGn model gives $\beta = 2 - 2H$, or

$$H = 1 - \beta/2. \tag{2}$$

[1] A flexible model of heavy tail from a view of fractional lower-order statistics discussed by Chen, Sun, and Zhou [63] is worth noting.