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A novel flux-fluctuation law for network with self-similar traffic

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HIGHLIGHTS

- A flux-fluctuation law of self-similar traffic is derived on Pareto ON/OFF model.
- Numerical simulations illustrate the validity of the novel law.
- The law is further demonstrated in GEANT network with actual traffic data.
- The effect of internal factor on the law is positively related to self-similarity.
- The effect of external network load on the law is determined by a single parameter.

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ABSTRACT

The actual network traffic can show self-similar and long-range dependent features, however, the revealed flux-fluctuation laws are only applicable to networks with short-range dependent traffic. In this paper, we propose an improved theoretical flux-fluctuation law of the self-similar traffic based on Pareto ON/OFF model. The proposed law shows that (i) the greater the self-similarity is, the stronger the influence of the internal factor is; (ii) the influence of the external factor is only determined by a single parameter characterizing the external network load. Numerical simulations illustrate the validity of the proposed flux-fluctuation law under diverse network scales and topologies with various self-similarity of traffic and time windows. We also demonstrate the effectiveness of the proposed law on the actual traffic data in the real GEANT network. As compared to the existing laws, the flux-fluctuation law proposed in this paper can better fit the actual variation of self-similar traffic and facilitate the detection of nodes with abnormal traffic.

1. Introduction

Traffic is an important factor affecting the performance, reliability and robustness of a network. Therefore understanding the fluctuation law of traffic is meaningful to the design, control and optimization of networks [1]. In early times, considerable efforts concerning traffic flow in complex networks were dedicated to the determination of bounds of network conditions leading to congestion, and the fluctuation of traffic is determined by the congested traffic [2–4]. However, through

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the network design and control, congestion can usually be avoided. Thus, the fluctuation of traffic is not really driven by the congestion process but by behavior of the "normal" traffic. Hence it is not accurate or adequate to describe the fluctuation law based on the analysis of the process that turns the network from a free-flow state into a congestion state. Numerous efforts have been expended in studying the relationship between the mean and variance of the network traffic [5–10] to understand the traffic law.

The *power-law* scaling is widely revealed in the degree distribution of actual networks [11,12] and used in modeling network structures [13,14], some researchers find that the relationship between the mean and variance of the network traffic also follows a power-law scaling [5–7]. Particularly, Menezes and Barabási [5,6] proposed a model to understand the origin of traffic fluctuations in a number of real world systems (including the Internet, the World Wide Web, and highway networks) and claimed a power-law scaling relationship between the mean and variance of the traffic, where the power-law exponent can take on a finite set of discrete values, such as 0.5 or 1. Later on Duch and Arenas [7] analyzed the real traffic in the Abilene backbone network and found that the power-law exponent can actually assume continuous values in the range of [0.5, 1]. Recent studies however revealed another *non-power-law* type relationship between the mean and variance of network traffic [8–10]. For example, Meloni et al. found such a non-power-law relationship between the two quantities based on analytical arguments and numerical results support from both simulated systems and a realistic communication network system [8]. The non-power-law in Ref. [8] was derived based on the assumption that the traffic arrival process to each node follows a Poisson distribution. With the same assumption on the Poisson arrival process to nodes, Zhou et al. [9] revealed the similar non-power-law for networks with average network traffic load following different distributions. These laws are mostly applicable to the Poisson traffic model, which is appropriate for the short-range dependent traffic.

In 1994 Leland et al. found the self-similar feature of the Ethernet traffic [1], which shows the actual traffic exhibits correlations over a wide range of time scales (i.e., has long-range dependence). Such feature has been further proved to be the most important feature of network traffic [15–17]. The traditional traffic models (e.g., the Poisson traffic model [18], Autoregressive moving average traffic model [19], Markov traffic model [20]), however typically involve a very limited range of time scales (short-range dependence in nature) and cannot reflect the self-similar feature of the actual traffic [15,21]. Therefore the traditional traffic models are not applicable to analyzing the fluctuation law of the self-similar traffic.

In this paper, we make new contributions by studying relationship between mean and variance of the self-similar traffic and address the universality of the law as being applied to general complex networks. The law is derived based on a self-similar traffic model called Pareto ON/OFF model and is validated using simulations under diverse network scales and topologies with various self-similarity of traffic and time windows. Effectiveness of the proposed law is also demonstrated on the actual traffic data in the real GEANT network.

The remainder of this paper is organized as follows. In Section 2, we briefly introduce the ON/OFF traffic model adopted in this work to generate self-similar traffic. The flux-fluctuation law is derived in Section 3, and influences of internal dynamic and external dynamic on the flux-fluctuation are discussed. To demonstrate effectiveness of the proposed flux-fluctuation law, numerical simulations under general network scales and topologies with various self-similarity of traffic and time windows are conducted in Section 4. In Section 5, we analyze the real traffic in GEANT network to further verify the effectiveness of the proposed law. Finally concluding remarks are provided in Section 6.

2. ON/OFF self-similar traffic model

Different self-similar traffic models have been proposed in literature. Examples include heavy-tailed ON/OFF model [16], wavelets model [17] and α-stable traffic model [22]. Among these models, the heavy-tailed ON/OFF model provides a physical explanation of the self-similar feature of traffic and has been widely used to generate self-similar traffic due to its mathematical simplicity.

As detailed in Leland et al. [21], the heavy-tailed ON/OFF model regards the network similarity process as the result of superposition of multiple traffic flows generated from different source nodes. It assumes that the source alternates between an ON-period and an OFF-period. During the ON-period, packets are generated and sent from the source to the destination at a constant rate v, while during the OFF-period, no packets are transmitted.

Suppose there are M identically independently distributed (i.i.d.) ON–OFF sources. To specify the distributions of durations of the ON-period and OFF-period, let $f_1(x)$, $F_1(x)$, $F_{1c}(x)$, μ, σ_1^2 denote the probability density function, cumulative distribution function, complementary distribution function, mean length and variance of the duration of an ON-period; and correspondingly we have $f_2(x)$, $F_2(x)$, $F_{2c}(x)$, μ, σ_2^2 characterizing the duration of OFF-period. Assume as $x \to \infty$, either

$$F_{1c}(x) \sim l_1 x^{-\alpha_1} L_1(x) \quad \text{with } 1 < \alpha_1 < 2 \text{ or } \sigma_1^2 < \infty$$

and

$$F_{2c}(x) \sim l_2 x^{-\alpha_2} L_2(x) \quad \text{with } 1 < \alpha_2 < 2 \text{ or } \sigma_2^2 < \infty$$

where $l_j > 0$ is a positive constant and $L_j > 0$ is a slowly varying function at infinity. Additionally, when $1 < \alpha_j < 2$, set $a_j = l_j \Gamma((2-\alpha_j)/(\alpha_j - 1))$; when $\sigma_j^2 < \infty$, set $\alpha_j = 2$, $L_j \equiv 1$ and $a_j = \sigma_j^2$. Let t denote the time and T represent a time rescaling factor. Then for large values of T and M, the aggregate cumulative traffic in interval $[0, Tt]$ behaves statistically