

## Scaling Breakdown in Flow Fluctuations on Complex Networks

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We propose a model of random diffusion to investigate flow fluctuations in complex networks. We derive an analytical law showing that the dependence of fluctuations with the mean traffic in a network is ruled by the delicate interplay of three factors, respectively, of dynamical, topological and statistical nature. In particular, we demonstrate that the existence of a power-law scaling characterizing the flow fluctuations at every node in the network cannot be claimed. We show the validity of this scaling breakdown under quite general topological and dynamical situations by means of different traffic algorithms and by analyzing real data.

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Communication networks [1] are nowadays the subject of intense research as modern society increasingly depends on them. On the one hand, the first studies have dealt with the architecture of these systems, showing that the systems' topological features [1–3] are at the root of the critical behavior of several dynamical processes taking place on top of them [1,4]. On the other hand, models for traffic and information flow on complex networks have been recently investigated as a way to improve our understanding on key issues such as the scalability, robustness, performance, and dynamics of technological networks [1,4]. In particular, much effort has been invested in finding what are the conditions for an efficient performance of communication networks, the latter being measured as the ability of the system to avoid congestion and reduce transit times [5–8]. Nevertheless, large communication networks such as the Internet usually avoid the regime in which congestion arises, and therefore the dynamics of packets is not driven by congestion processes. Instead, the fluctuations in traffic flow constitute the main factor affecting the dynamics of these communication systems.

The relationship between the fluctuations  $\sigma$  and the average flux  $\langle f \rangle$  in traffic dynamics on complex networks is a controversial issue that has received a lot of attention very recently [9,10]. The authors of Refs. [9,11] claimed the existence of the relation  $\sigma \sim \langle f \rangle^\alpha$ , with real communication networks belonging to one of two universality classes, the first one characterized by an exponent value  $\alpha = 1/2$ , the second one by  $\alpha = 1$ . The authors of [10] questioned the existence of the two universality classes. They numerically showed that there is a wide spectrum of possible values for  $\alpha$ , depending on parameters such as the persistence of packets in the network, the duration of the time window during which statistics are recorded, and the rate of service at the nodes' queues [10].

In this Letter, we propose a model for traffic in complex networks, the Random Diffusion (RD) model, that is amen-

able to analytical solution. The model predicts the existence of a simple law that relates the fluctuations at a node  $i$ ,  $\sigma_i$  to the average traffic flow  $f_i$ , depending on the delicate balance of three quantities: (i) the variation in the number of packets in the network, (ii) the degree of the node  $i$ , and (iii) the length of the time window in which measures of traffic flow are performed. Notwithstanding its simplicity, the RD model is able to capture the essential ingredients determining the scaling of fluctuations empirically observed for traffic flow in real complex networks. More important, we also show that the hypothesis of a *power-law scaling* of flow fluctuations has to be abandoned under certain conditions. Results of numerical simulations of a traffic-aware model and analysis of real data of Internet flow confirm our theoretical findings.

In the random diffusion (RD) model, we represent packets of information as  $w$  random walkers traveling in a network made up of  $N$  nodes and  $K$  links. Under the assumption that the packets are not interacting, it follows that the average number of walkers  $\lambda_i$  at a node  $i$  is given, in the stationary regime, by [12,13]

$$\lambda_i(w) = \frac{k_i}{2K} w. \quad (1)$$

Let us assume that the total observation time  $T$  is divided into time windows of equal length. Each window is made of  $M$  time units. A window represents the minimal resolution for measurements of the flux in a node and its fluctuations, being the first the result of accumulating the number of packets traveling through the node during the  $M$  time units. The average number of packets  $\langle f_i \rangle$  processed by node  $i$  in a time window is measured, together with its standard deviation  $\sigma_i$ . These are the two quantities monitored in Refs. [9,10] for real systems and in the numerical simulations of network traffic models. The main interest is to investigate the dependence of  $\sigma_i$  with  $\langle f_i \rangle$ . In particular, we want to verify whether a power-law relation  $\sigma_i \sim \langle f_i \rangle^\alpha$

holds, and what factors determine the exponent  $\alpha$ . In the RD model, we can consider two possible situations: either the number of packets in the network is constant over the whole period of time  $T$ , namely  $w = W$ , or it can vary from one time window to the other. In the latter situation, we assume that the probability  $F(w)$  of having  $w$  walkers on the network in a window of length  $M$  is equally distributed in the range  $[W - \delta, W + \delta]$ , i.e.,

$$F(w) = \frac{1}{2\delta + 1}, \quad (2)$$

with  $1 \leq \delta \leq W$ . To find an expression for the average number of packets  $\langle f_i \rangle$  flowing through a given node  $i$ , we first calculate the probability  $P_i(n)$  that, after  $M$  time steps,  $n$  packets have visited node  $i$ .

In the case  $w = W$ , due to the fact that the packets are not interacting, the arrival of walkers at a node is a Poisson process. Therefore, after a period of  $M$  time units, the mean number of packets (the average flux) at a node  $i$  is  $\langle f_i \rangle = \lambda_i(w)M$ , and the probability of having  $n$  packets reads

$$P_i(n) = e^{-\lambda_i(w)M} \frac{[\lambda_i(w)M]^n}{n!}, \quad (3)$$

with  $\sigma = \sqrt{\lambda_i(w)M} = \sqrt{\langle f_i \rangle}$ . Thus, the scaling exponent is  $\alpha = 1/2$ .

In the more general case in which the number  $w$  is distributed as in Eq. (2), the probability  $P_i(n)$  is

$$P_i(n) = \sum_{j=0}^{j=2\delta} \frac{e^{-(k_i/2K)(W-\delta+j)M} \left[ \frac{k_i}{2K}(W-\delta+j)M \right]^n}{2\delta+1 n!}. \quad (4)$$

Calculating first and second moments of  $P_i(n)$ , one obtains

$$\langle f_i \rangle = \sum_{n=0}^{\infty} n P_i(n) = \frac{k_i W M}{2K}, \quad (5)$$

$$\langle f_i^2 \rangle = \sum_{n=0}^{\infty} n^2 P_i(n) = \langle f_i \rangle^2 \left( 1 + \frac{\delta^2}{W^2} \right) + \langle f_i \rangle. \quad (6)$$

Finally, the standard deviation can be expressed as a function of  $\langle f_i \rangle$  as

$$\sigma_i^2 = \langle f_i \rangle \left( 1 + \langle f_i \rangle \frac{\delta^2}{W^2} \right). \quad (7)$$

The above derivation provides an understanding of the origins of Eq. (7), proposed in [9], and shows that the relation between  $\sigma_i$  and  $\langle f_i \rangle$  depends on the concurrent effects of three factors, namely: (i) the noise  $\delta$  associated to the fluctuations in the number of packets in the network from time window to time window; (ii) the length  $M$  of the time window; and (iii) the degree of the node  $k_i$  (since  $\langle f_i \rangle$  depends on  $k_i$ ). Consequently, real traffic rarely falls in either of the two limiting cases of Eq. (7), i.e.,  $\sigma \sim \langle f \rangle^\alpha$  with  $\alpha = 1/2$  or 1.

Expression (7) contains all the behaviors previously observed in Refs. [9,10], and also predicts new dependencies that can be tested to be valid in more refined traffic

models as well as in real data. In fact, if the three quantities  $\delta$ ,  $M$ , and  $k_i$  are such that

$$\frac{k_i M \delta^2}{2KW} \ll 1, \quad (8)$$

expression (7) reduces to a power-law scaling  $\sigma \sim \langle f \rangle^\alpha$  with exponent  $\alpha = 1/2$ . On the contrary, whenever the ratio  $\frac{k_i M \delta^2}{2KW}$  is not negligible anymore, the exponent  $\alpha$  differs from  $1/2$  and approaches 1. In other words, it may well be the case in which, even for small values of the noise parameter  $\delta$ , a large value of  $M$  cancels out the effect of the ratio  $\frac{\delta}{W}$  being too small in Eq. (7). This behavior was already explored in [10] by means of numerical simulations. However, the fact that the ratio in formula (8) depends quadratically on  $\delta$  and only linearly on  $k_i$  and  $M$ , has gone unnoticed. The RD model puts such dependence on solid theoretical grounds, and also reveals the role played by the other two parameters  $M$  and  $k_i$  on the observed scaling.

In Fig. 1, we plot the dependence of  $\sigma$  with  $\langle f \rangle$  in the RD model for several values of the parameters  $M$  and  $\delta$ . Panel (a) corresponds to the case in which the ratio  $\frac{\delta}{W} = 10^{-1}$  is fixed and the length of the time windows used to measure

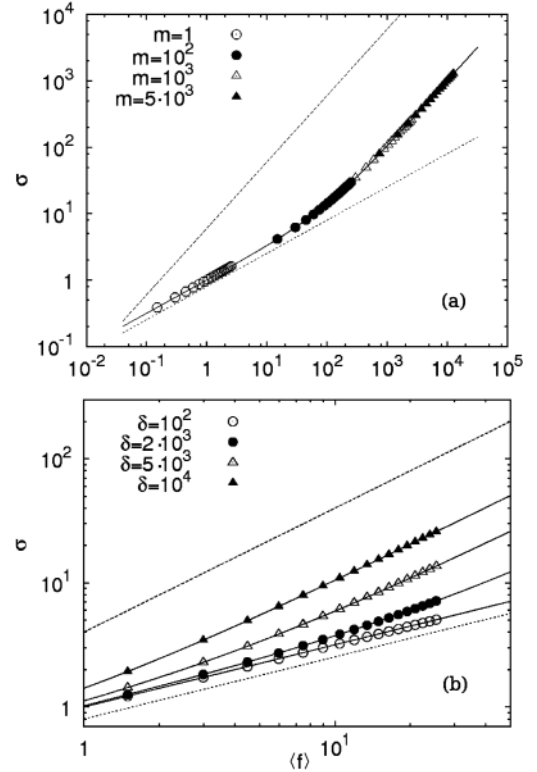


FIG. 1. Flow fluctuation  $\sigma$  as a function of  $\langle f \rangle$  for the RD model with various parameter values. In panel (a),  $\delta = 10^3$  and  $W = 10^4$ . In panel (b),  $W$  has the same value while  $M$  has been fixed to 10. In both figures, points correspond to the solution of Eq. (7) for different values of  $k_i$  (1...18). The total number of links is  $K = 33500$ . Dashed lines are guides to the eyes and correspond to  $\sigma \sim \langle f \rangle^\alpha$ , with  $\alpha = 1/2$  (lower curves) and  $\alpha = 1$  (upper curves). See the text for further details.

the flow of packets through different nodes is varied. For each value of  $M$ , we have superimposed the results obtained for nodes with different connectivity values, ranging from  $k_i = 1$  to  $k_i = 18$ . If one follows the arguments given in [9], a value of  $\alpha = 1/2$  should be expected for this choice of  $\delta/W$ . Instead, as shown in the figure,  $\sigma \sim \langle f \rangle^{1/2}$  only for small values of  $M$ , while the scaling exponent approaches 1 as  $M$  is increased. This means that, whenever the temporal resolution in the measurements is not small enough and packets are counted and accumulated over long periods,  $\alpha$  tends to 1.

A novel striking feature revealed by law (7), and not revealed in previous studies, is the dependence with the degree of the nodes. An example of the effects of node degrees is shown in Fig. 1(a). It turns out that, for some values of  $M$  (e.g.,  $M = 10^2$  in the figure), the fluctuations at lowly connected nodes are characterized by an exponent  $\alpha = 1/2$ , whereas for highly connected nodes, the exponent turns out to be  $\alpha = 1$ . Hence, there is not a single exponent characterizing the fluctuations at *every* node of the network, regardless of its connectivity. This is again a clear indication that a power-law behavior,  $\sigma \sim \langle f \rangle^\alpha$ , even with nonuniversal exponents ranging in  $[1/2, 1]$ , is not the most general situation when characterizing the flow fluctuations for a whole network [9,10]. Admittedly,  $\alpha$  is not constant for every possible choice of the parameters  $\delta$ ,  $W$ , and  $M$  along the whole set of  $k_i$  values. This effect is particularly relevant for highly heterogeneous networks like the Internet, where degree classes span several decades. In these kinds of networks, one should therefore expect different scaling laws depending on whether the packets are flowing through lowly or highly connected nodes.

The influence of the noise level on  $\alpha$  for a fixed time window length ( $M = 10$ ) is depicted in Fig. 1(b). When  $\delta$  is small, so that the number of packets in the network from one time frame to the following does not change significantly,  $\alpha = 1/2$ . On the contrary, when  $\delta$  is sufficiently large, the exponent is 1. This is more in consonance with the results in [9], where the dependence with the noise level was addressed only for a low value of  $M$ , getting that as  $\delta$  increases  $\alpha \rightarrow 1$ . On the other hand, we observe again that fixing  $M$  and varying  $\delta$  does not guarantee the existence of a unique exponent for the scaling of fluctuations in traffic flow, though in this case the dependence is smoother than that observed in Fig. 1(a).

In the following, we show that expression (7) predicted by the RD model is indeed valid for more elaborated traffic models and that the RD approximation captures the phenomenology of real communication systems. We report the results obtained on top of synthetic scale-free (SF) networks with  $N = 10^4$  nodes and power-law degree distributions  $p_k \sim k^{-\gamma}$ , with an exponent  $\gamma = 2.2$  as the one empirically observed for the Internet at the autonomous system level [2]. However, we stress that since the topological properties of the underlying graph only enter into Eq. (7) through the degree of the nodes  $k_i$  and the total

number of links in the network,  $K$ , the results hold for any graph with an arbitrary degree distribution  $p_k$  as our own simulations using SF networks, random graphs, and a real autonomous system map of the Internet [2] reveal.

On the other hand, to mimic the way packets flow in real communication networks, we consider a dynamical model that is able to simulate the Internet's most important dynamical characteristics [6,7]. The dynamics of the packets is simulated as follows. Each node represents a router with an infinite size buffer. The delivery of packets is made following a First In First Out (FIFO) policy. At each time step,  $p$  new packets are introduced in the system with randomly chosen sources and destinations [14]. Packets routing is based on a traffic-aware scheme [6,7] in which the path followed by a packet is the one that minimizes the effective distance  $d_{\text{eff}}^i = h d_i + (1 - h) c_i$ , where  $d_i$  is the distance between node  $i$  and the packet destination,  $c_i$  is the number of packets in  $i$ 's queue, and  $h$  is a tunable parameter that accounts for the degree of traffic awareness incorporated in the delivery algorithm [6,7]. It is worth recalling that  $h = 1$  recovers a shortest-path delivery protocol, mimicking most of the actual Internet routing mechanisms.

Figure 2 shows  $\sigma$  as a function of  $\langle f \rangle$  obtained through extensive numerical simulations of the traffic model with  $h = 1$  and  $p = 2$ . Different panels in the figure correspond to different values of the time-window length  $M$ . The results indicate that the main responsible of the value of  $\alpha$  (interpolating between the two extreme  $\alpha = 1/2$  and  $\alpha = 1$ ) is the interplay between the node degree and the time resolution used to record the flux of packets, exactly as predicted by the scaling law (7) obtained in the RD model. In fact, Fig. 2(a) corresponds to the choice of parameters for which formula (8) holds for all values of  $k_i$ , leading to  $\alpha = 1/2$ . On the contrary, when  $M$  is large enough and the other parameters are kept fixed as in

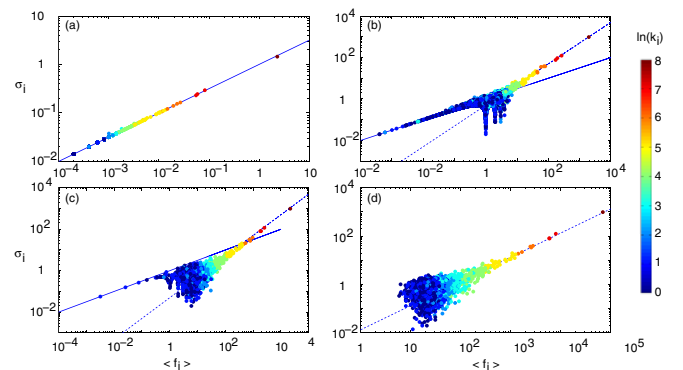


FIG. 2 (color online). Flow fluctuation  $\sigma$  as a function of  $\langle f \rangle$  from numerical simulations of the Internet traffic model (see text for details) on synthetic scale-free networks with  $N = 10^4$  nodes,  $K = 37551$  links, and degree exponent  $\gamma = 2.2$ . Different panels correspond to different values of  $M$ , respectively  $M = 1, 5 \times 10^2, 35 \times 10^3, 10^5$ . Color-coded values represent the logarithm of node degree. The continuous line is the curve  $y = x^{0.5}$ , while the dashed line is  $y \sim x$ .

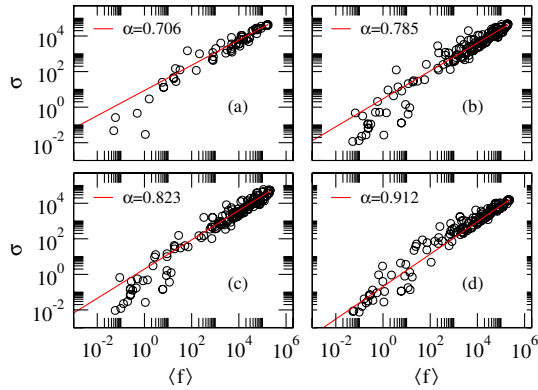


FIG. 3 (color online). Flow fluctuation  $\sigma$  as a function of  $\langle f \rangle$  for the Abilene Interfaces. The values of  $M$  used in each panel are:  $M = 5$  (a),  $M = 30$  (b),  $M = 60$  (c), and  $M = 720$  (d). Time is in minutes. The value of  $\alpha$  for each  $M$  is also reported. Averages are taken over one month of data corresponding to the period between January 11 to February 11 of 2006.

Fig. 2(d), relation (8) is not satisfied whatever the value of  $k_i$  used, hence giving an exponent  $\alpha = 1$ . Finally, the breakdown of the scaling law  $\sigma \sim \langle f \rangle^\alpha$  anticipated by the RD model is captured in Figs. 2(b) and 2(c), where it is clearly revealed that there is not a unique exponent characterizing the flow of packets through *every* node of the network. Indeed, there is a crossover from  $\sigma \sim \langle f \rangle^{1/2}$  for lowly connected nodes to  $\sigma \sim \langle f \rangle$  for the highly connected ones. We also note that a similar behavior is observed (figures not shown) when traffic-aware routings ( $h < 1$ ) are taken into account.

Finally, we have also analyzed the data corresponding to the traffic between routers of the Abilene backbone network [15]. As the data collected for the routers in the backbone correspond only to the flow between them, this backbone network can be viewed as an isolated communication system where the routers create, deliver, and receive data packets. Therefore, the measures effectively correspond to a small network handling a large amount of traffic and with all its nodes having a similar degree. For this reason, we are not able to observe here the dependence with the node degree. However, at variance with the analysis performed in [10], we have varied the length of the time windows used to extract the flux and its deviation [16]. Once again, the results, depicted in Fig. 3, show that the exponent  $\alpha$  is not universal and radically depends on  $M$ . Note that, although the lower bound of  $\alpha = 0.706 > 1/2$  is determined by the minimal resolution ( $M = 5$  minutes) of the raw data, further increasing  $M$  will recover the upper bound  $\alpha = 1$ .

In summary, in this Letter, we have derived a theoretical law for the dependence of fluctuations with the mean traffic in a network. Such a dependence is governed by three factors: one related to the dynamics, one related to the topology, and one of statistical nature. More importantly, the theoretical law reveals that the previously claimed power-law scaling (with universal or nonuniversal expo-

nents) has to be abandoned. Our numerical results and the analysis of real data confirm that, even in the presence of correlations between packets, one cannot assume a single exponent to characterize the fluctuations of traffic for the whole network. Finally, we note that the scaling breakdown predicted here is amenable to experimental confirmation by measuring the traffic flow in large communication networks to capture the predicted (topological) effects of degree heterogeneity.

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- [14] We have checked that the behavior observed does not depend on the creation rate of packets, by considering uniform, exponential, and power-law distribution functions (in all cases, the distributions are characterized by the same average number of packets  $p$ ).
- [15] Data publicly available at <http://abilene.internet2.edu>.
- [16] We are implicitly assuming that packets are uncorrelated. This approximation seems not too crude as the lifetime of packets in the Internet is at most of several seconds, while the minimal resolution of the raw data is 5 minutes. After all, the 5 minutes time window can also be considered as cumulative data. We have, however, redone the calculations taking nonconsecutive time windows to further avoid possible correlations with no qualitative changes in the results.