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The gradually truncated Lévy flight: stochastic process for complex systems

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Abstract

Power-law distributions, i.e. Lévy flights have been observed in various economical, biological, and physical systems in high-frequency regime. These distributions can be successfully explained via gradually truncated Lévy flight (GTLF). In general, these systems converge to a Gaussian distribution in the low-frequency regime. In the present work, we develop a model for the physical basis for the cut-off length in GTLF and its variation with respect to the time interval between successive observations. We observe that GTLF automatically approach a Gaussian distribution in the low-frequency regime. We applied the present method to analyze time series in some physical and financial systems. The agreement between the experimental results and theoretical curves is excellent. The present method can be applied to analyze time series in a variety of fields, which in turn provide a basis for the development of further microscopic models for the system. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The availability of high-frequency data for financial [1–8], biological [9–11] and physical [12–21] systems has enabled the study of these systems on very small scale. Lévy flight [22,23], i.e. a power-law distribution, has been observed in many systems. A Lévy flight is a random walk whose step length occurs with a power-law frequency in contrast to a conventional random walk for which larger steps are exponentially rare [24]. The fact that many natural phenomena must be described by power-law statistics

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has only been accepted in the past decade [25,26]. Correspondingly, an intense activity has developed in order to understand both the physical content of the mathematical tools devised by P. Lévy and others [12,22,23] and the origin of these ubiquitous power law tails. This has led to the concept of self-organized criticality [27,28]. Tsallis et al. [29–32] extended Boltzmann–Gibbs statistics to a Generalized Statistical Mechanics and Thermodynamics to consider long-range jumps and were able to provide a strong theoretical support for describing processes with power-law statistics.

Lévy flights have infinite variance which discourages a physical approach and an unavoidable cut off is always present which is explained through boundary conditions or spatio-temporal coupling or some similar mechanisms.

Mantegna and Stanley [33], introduced the truncated Lévy flight (TLF) to solve the problem of infinite variance, in which the probability of taking a step is abruptly cut to zero at a certain critical step size. Koponen [34] discussed the problem of convergence of TLF towards the Gaussian stochastic process, in which, he gradually truncated the probability distribution from the beginning. In real systems the distribution is given very well through Lévy distribution for smaller and larger steps. It fails only for extremely large steps, which means that we need to cut only the extremely large steps. Physically, we can justify it as a gradual decrease of positive feedback for very large steps due to physical limitations of the system. The positive feedback is responsible for fatter tails in Lévy distribution. Recently, Gupta and Campanha [35] proposed a new stochastic distribution, the gradually truncated Lévy flight (GTLF) for these systems in high-frequency regime. In the GTLF, the probability distribution is cut-off gradually only after a certain critical length. The GTLF model approximates better probability distribution in real systems. The GTLF has finite variance and an analytical solution in a closed form is possible.

It is a general tendency in these systems to approach a Gaussian distribution in the large scale i.e. in the low-frequency regime. This is also expected here via the central limit theorem (CLT), which is fundamental to statistical mechanics [24] and states that the summation

$$z_n = \sum_{i=1}^n x_i \quad (1)$$

of n stochastic variables $\{x\}$ that are statistically independent, identically distributed and, with a finite variance, converges to a normal (Gaussian) stochastic process when $n \rightarrow \infty$. x_i is the step size of the i th observation. Thus in order to analyze completely a system with power-law distribution in a closed form, it is important to develop a statistical distribution in which a controlling mechanism is incorporated in the distribution itself to discourage larger steps such that:

- (i) Variance is finite.
- (ii) The probability of taking a step decreases gradually and not abruptly with the step size.
- (iii) The distribution gives rise to power-law distribution in high-frequency regime, while approaches to a Gaussian (normal) distribution in low-frequency regime.

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