Research paper

Symbolic phase transfer entropy method and its application

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A B S T R A C T

In this paper, we introduce symbolic phase transfer entropy (SPTE) to infer the direction and strength of information flow among systems. The advantages of the proposed method are investigated by simulations on synthetic signals and real-world data. We demonstrate that symbolic phase transfer entropy is a robust and efficient tool to infer the information flow between complex systems. Based on the study of the synthetic data, we find a significant advantage of SPTE is its reduced sensitivity to noise. In addition, SPTE requires less amount of data than symbolic transfer entropy (STE). We analyze the direction and strength of information flow between six stock markets during the period from 2006 to 2016. The results indicate that the information flow among stocks varies over different periods. We also find that the interaction network pattern among stocks undergoes hierarchical reorganization with transition from one period to another. It is shown that the clusters are mainly classified according to period, and then by region. The stocks during the same time period are shown to drop into the same cluster.

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1. Introduction

It is a general topic of common interest to understand the information flow between nonlinear systems [1–6]. More specifically, it includes two important indicators: the direction and strength. The transfer entropy which measures the information flow between nonlinear systems has been recently introduced by Schreiber [7], A. Kaiser and T. Schreiber [8], F. Verdes [9] and Y. Kuniiyoshi [10] point out that all kinds of technologies have been proposed to estimate the transfer entropy from the observed values [11–16]. However, most of the technologies highly require for data, need to adjust parameters, and are sensitive to noise. The shortcomings hinder the wide application of transfer entropy in various fields.

In 2008, M. Staniek and K.K. Lehnertz numerically illustrate that symbolic transfer entropy in quantifying dominating direction of information flow between time series from coupling system of the same and different structure [17], is a powerful and fast calculation method. These features make the symbolic transfer entropy a promising method in data analysis. Through investigation and study on the numerical and brain electrical activity time series analysis, it is found that asymmetric dependence between the same and different structure, but not fully synchronous coupling system.

M. Lobier, F. Siebenhaller, S. Palva and J.M. Palva propose phase transfer entropy (Phase TE) as a measure to infer the direct relationship between neural oscillations [18]. Phase TE is a new, phase-based measure of directed connectivity. Moreover, they find that Phase TE detects the strength and direction of the connections even in the presence of vast amounts of noise and linear mixed. Phase TE is robust to nuisance parameters and more efficient computationally. Phase TE

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detects connectivity between time series across a range of analysis lag. Finally, because Phase TE is similar to phase-specific functional connectivity metrics, it could identify information flow of limited frequency band. Those indicate that Phase TE is suitable for estimates of the direct connections based on the Phase.

Therefore, considering of faults and the bottleneck problem in the study of transfer entropy method, this paper proposes the improved method of transfer entropy to overcome the limitations of existing methods, which is novel in detection of the information flow among nonlinear systems. This paper intends to study symbolic phase transfer entropy based on the transfer entropy method, which is used to quantify the direction and strength of information flow among systems and applied to the experiment analysis for synthetic data and real-world data. This paper mainly uses symbolic phase transfer entropy to study nonlinear causality among the stocks.

In this paper, we quantify symbolic phase transfer entropy among DAX, FTSE, S&P500, NAS, ShangZheng and ShenCheng stock closing prices. In order to accurately test the validity of proposed method, we consider time series generated by AR model, ARFIMA model and Henon map. The proposed SPTE method is shown to cater for detecting the direction and strength of information flow among systems.

The rest of the paper is organized as follows. In Section 2, we introduce symbolic transfer entropy method and symbolic phase transfer entropy method in detail. In Section 3, we provide artificial data and real stock data. Analysis and results for data are shown in Section 4. The conclusions are presented at the last section.

2. Methodology

2.1. Symbolic transfer entropy

The method of symbolic transfer entropy is based on the phase space reconstruction and associated with the definition of permutation entropy [19]. For an arbitrary i, X(i) = {x(i), x(i+1),...,x(i+(m−1)l)} got by phase space reconstruction are arranged in an ascending order {x(i+(k_1−1)l), x(i+(k_2−1)l),...,x(i+(k_m−1)l)}, where l is the time delay, and m denotes the embedding dimension. In case of equal values, for example, while x(i+(k_1−1)l) = x(i+(k_2−1)l) we write x(i+(k_1−1)l) ≤ x(i+(k_2−1)l) if k_1 ≤ k_2, therefore we insure that every X_i is uniquely mapped onto one of the m! possible permutations. A symbol is thus defined as \( \tilde{x}_i = (k_1, k_2, ..., k_m) \), and with the relative frequency of symbols we estimate joint and conditional probabilities of the sequence of permutation indices. Given two time sequences \( \{x_i\} \) and \( \{y_i\} \), we define symbolic transfer entropy as

\[
T^\delta_X = -\sum \left( p(\hat{x}_{i+\delta}, \hat{y}_i) \log p(\hat{x}_{i+\delta} | \hat{x}_i) + p(\hat{x}_{i+\delta}, \tilde{y}_i) \log p(\hat{x}_{i+\delta} | \tilde{y}_i) \right)
\]

where

\[
p(\hat{x}_{i+\delta} | \hat{x}_i) = \frac{p(\tilde{x}_{i+\delta}, \hat{y}_i)}{p(\tilde{x}_i | \hat{y}_i)}
\]

(2)

\[
p(\hat{x}_{i+\delta} | \tilde{y}_i) = \frac{p(\tilde{x}_{i+\delta}, \tilde{y}_i)}{p(\tilde{x}_i | \tilde{y}_i)}
\]

(3)

where the sum runs over all symbols and \( \delta \) denotes a time step. \( T^\delta = T^\delta_{YX} - T^\delta_{XY} \) qualifies the direction of information flow between X and Y. If the value of \( T^\delta \) is positive, the direction of information flow is from Y to X. On the contrary, the direction of information flow is from X to Y. The value represents the strength of information flow.

2.2. Symbolic phase transfer entropy

The symbolic phase transfer entropy is symbolic transfer entropy based on phase. That is to say, before we deal with the ordinary time series, we extract phase time series from the original time series. Then we deal with the phase time series. Therefore, we define symbolic phase transfer entropy in the following steps.

Step 1: For the given time series X(i) and Y(i), its instantaneous phase time-series \( \theta_X(t) \) and \( \theta_Y(t) \) is separately obtained by \( X(i) \) and \( Y(i) \) with Hilbert transform [20]. For the given time series x, its analytic series \( \zeta \) is defined as

\[
\zeta(t) = x(t) + j\hat{x}(t) = A(t)e^{\phi(t)}
\]

(4)

\[ x(t) \text{ with Hilbert transform gets } \hat{x}(t) \]

\[
\hat{x}(t) = \frac{1}{\pi} \text{PV} \cdot \int_\infty^{\infty} \frac{x(t)}{t - \tau} d\tau
\]

(5)

PV. denotes the integral of the Cauchy principal value. In Eq. (4), \( A(t) \) is the instantaneous amplitude and \( \theta(t) \) is the instantaneous phase of \( x(t) \).
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