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Analysis of local time-frequency entropy features for nonstationary signal components time supports detection

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ABSTRACT

Identification of different specific signal components, produced by one or more sources, is a problem encountered in many signal processing applications. This can be done by applying the local time-frequency-based Rényi entropy for estimation of the instantaneous number of components in a signal. Using the spectrogram, one of the most simple quadratic time-frequency distributions, the paper proves the local applicability of the counting property of the Rényi entropy. The paper also studies the influence of the entropy order and spectrogram parameters on the estimation results. Numerical simulations are provided to quantify the observed behavior of the local entropy in the case of intersecting components. The causes of decrements in the local number of time supports in the time-frequency plane are also studied. Finally, results are provided to illustrate the findings of the study and its potential use as a key step in multicomponent instantaneous frequency estimation.

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1. Introduction

Nonstationary signals encountered in engineering applications (civil, military, biomedical) are often characterized by multiple components with varying spectral contents. Different signal components may have overlapping time supports, making the classical time representation inadequate to correctly identify the energy contribution of each component. Similarly, the frequency representation fails to correctly map the spectral energy of different components if they share frequency content. Joint time and frequency representations, being energy distributions showing the signal local frequency content, overcome such limitations of the classical signal representations [1]. These time-frequency distributions allow the isolation of different spectral components that are present in a signal, as well as their respective instantaneous frequencies [2]. The number of components that are present in a signal can thus be visually identified. However, for applications requiring the automated assessment of the number of components, objective criteria are needed.

Applications such as classification, require time-frequency features that can be used for pattern recognition as an aid to identification and detection. A simple but efficient feature is the measure of complexity, which is extensively reviewed in this paper and applied to the estimation of the number of components in a signal.

For blind source separation algorithms, based on peaks extraction and tracking from TFDs, the key information is the local number of components, i.e. the instantaneous number of components supported in time. The recently introduced Short-term Rényi entropy [3] provides reliable information about the time support of different components, and thus can be used as the input information to peak detection and extraction techniques [1,4]. The Short-term Rényi entropy, as an indicator of the local number of time supported components, is discussed in Section 2. The simplified model presented in [3] doesn't clarify the role of the entropy order α and TFD features (local time and frequency supports) in the estimation. The Short-term Rényi entropy when applied to the spectrogram, being a widely used TFD, is therefore studied in Section 2. The analysis of particular situations occurring in nonstationary signals (ending/starting component, overlapping or intersecting components) is essential for correctly interpreting the information provided by the Short-term Rényi entropy, as explained in Section 3. Experimental results are provided in Section 4. In Section 5, the obtained results are discussed, and possible prospectives are considered.

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2. The Short-term Rényi entropy and the local component number estimation

2.1. The Rényi entropy of time-frequency distributions

Let's consider a multicomponent analytic signal with M components defined as

$$x(t)=\sum_{k=1}^{M}x_k(t), \tag{1}$$

with each of its component having the form

$$x_k(t)=a_k(t)e^{j\phi_k(t)}, \tag{2}$$

where $a_k(t)$ is the signal instantaneous amplitude, while the signal instantaneous frequency (IF) is defined as the time derivative of its instantaneous phase $\phi_k(t)$ [2]

$$f_k(t)=\frac{1}{2\pi}\frac{d\phi_k(t)}{dt}. \tag{3}$$

TFDs are expected to have highly resolved spectral components, while minimizing interferences. Maintaining highly concentrated components, while suppressing interferences [5] is a demanding task in the design of TFDs [6–10]. TFDs belonging to the Quadratic class are defined as [1,11]:

$$\rho_x(t,f)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(\nu,\tau)x\left(t+\frac{\tau}{2}\right)x^*\left(t-\frac{\tau}{2}\right) \times e^{j2\pi(\nu t-\nu u-f\tau)}\,du\,d\nu\,d\tau, \tag{4}$$

where $g(\nu,\tau)$ is the TFD kernel filter that defines the TFD and its properties. Some of the properties satisfied by the Quadratic TFDs, i.e. the preservation of the global signal energy in the (t,f) plane [1]

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\rho_x(t,f)\,dtdf=E_x, \tag{5}$$

and the time and frequency marginal conditions

$$\int_{-\infty}^{\infty}\rho_x(t,f)\,df=\left|x(t)\right|^2, \tag{6}$$

$$\int_{-\infty}^{\infty}\rho_x(t,f)\,dt=\left|X(f)\right|^2, \tag{7}$$

allow for a possible interpretation of a TFD as a pseudo-probability density function.

These assumptions allow the application of complexity measures from information theory to TFDs, such as the generalized entropy of Rényi [12]:

$$H_{\alpha,x}:=\frac{1}{1-\alpha}\log_2\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(\frac{\rho_x(t,f)}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\rho_x(t,f)\,df\,dt}\right)^{\alpha}dt\,df, \tag{8}$$

where the parameter α is the order of the Rényi entropy.

A useful property of the Rényi entropy is its counting property. If an ideal TFD, $I_x(t,f)$, of a two-component signal, $x(t)=x_1(t)+x_2(t)$ (where $x_2(t)$ is the time and/or frequency shifted copy of $x_1(t)$, and their respective TFDs are defined as $I_{x_1}(t,f)$, and $I_{x_2}(t,f)$) is

$$I_x(t,f)=I_{x_1}(t,f)+I_{x_2}(t,f)=I_{x_1}(t,f)+I_{x_1}(t-t_0,f-f_0), \tag{9}$$

then, the Rényi entropy of such TFD will result into

$$H_{\alpha,x_1+x_2} =\frac{1}{1-\alpha} \times\log_2\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(\frac{I_{x_1}(t,f)+I_{x_1}(t-t_0,f-f_0)}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}I_{x_1}(t,f)+I_{x_1}(t-t_0,f-f_0)\,df\,dt}\right)^{\alpha}dt\,df. \tag{10}$$

Under the assumption that $I_{x_1}(t,f)$ and $I_{x_1}(t-t_0,f-f_0)$ are compactly supported non-overlapping components in the (t,f) plane, the Rényi entropy will carry exactly one more bit of information when compared to the Rényi entropy of the TFD of one of the components [13], i.e.

$$H_{\alpha,x_1+x_2}=H_{\alpha,x_1}+1=H_{\alpha,x_2}+1, \tag{11}$$

so that the number of components $M=2$ can be estimated as

$$N=2^{H_{\alpha,x_1+x_2}-H_{\alpha,x_1}}=2^{H_{\alpha,x_1+x_2}-H_{\alpha,x_2}}=2. \tag{12}$$

In general, the number of estimated components N, in an M component signal with non-overlapping components, being represented by an ideal TFD, can be determined as

$$N=2^{H_{\alpha,x_1+x_2+\ldots+x_M}-H_{\alpha,x_m}}=M, \tag{13}$$

where $x_m(t)$ is an arbitrarily chosen component from the mixture. In order for Eq. (13) to hold, all signal components must exhibit the same time and frequency supports, i.e. all components must be replicas of the referent component $x_m(t)$, shifted in time and/or frequency [3,13]. Additionally, the reference components must be known by the signal analyst. These assumptions do not hold in general.

Recently, the Short-term Rényi entropy [3] has been introduced in order to overcome the above limitations of the global Rényi entropy as an estimator of the number of signal components. The Short-term Rényi entropy approach can precisely estimate the number of components that are present in a short time interval of a TFD, even for signals whose components present different time and frequency supports, and without prior knowledge of the signal as shown in [3,14].

Since the effective application of the global Rényi entropy requires signals whose components have equal time and frequency supports, the estimation by the local Rényi entropy exploits the fact that locally, in a short time interval Δt of a TFD, different components have equal frequency supports [3].

2.2. The stationary signal model

One of the most routinely used TFDs is the intuitive spectrogram, obtained as the squared magnitude of the Short-time Fourier transform (STFT). The kernel filter of the spectrogram can be expressed as [1]:

$$g(\nu,\tau)=\mathcal{F}_{t\to\nu}\left\{w\left(t+\frac{\tau}{2}\right)w\left(t-\frac{\tau}{2}\right)\right\}=A_w(\nu,\tau), \tag{14}$$

where $w(t)$ is the analysis window used in the Short-time Fourier transform.

However, the spectrogram suffers from limited time-frequency resolution, determined by the time and frequency supports of the

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