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Event-triggered sampling using signal extrema for instantaneous amplitude and instantaneous frequency estimation

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ABSTRACT

Event-triggered sampling (ETS) is a new approach towards efficient signal analysis. The goal of ETS need not be only signal reconstruction, but also direct estimation of desired information in the signal by skillful design of event. We show a promise of ETS approach towards better analysis of oscillatory non-stationary signals modeled by a time-varying sinusoid, when compared to existing uniform Nyquist-rate sampling based signal processing. We examine samples drawn using ETS, with events as zero-crossing (ZC), level-crossing (LC), and extrema, for additive in-band noise and jitter in detection instant. We find that extrema samples are robust, and also facilitate instantaneous amplitude (IA), and instantaneous frequency (IF) estimation in a time-varying sinusoid. The estimation is proposed solely using extrema samples, and a local polynomial regression based least-squares fitting approach. The proposed approach shows improvement, for noisy signals, over widely used analytic signal, energy separation, and ZC based approaches (which are based on uniform Nyquist-rate sampling based data-acquisition and processing). Further, extrema based ETS in general gives a sub-sampled representation (relative to Nyquist-rate) of a time-varying sinusoid. For the same data-set size captured with extrema based ETS, and uniform sampling, the former gives much better IA and IF estimation.

1. Introduction

Widely used signal sampling schemes can be classified as perfect signal reconstruction-driven sampling schemes; examples include conventional sampling schemes such as uniform sampling (sampling at greater than Nyquist-rate) [1], generalized uniform sampling [2], non-uniform sampling satisfying gap-density constraints [3], and compressive sampling [4]. These are designed on the premise of perfect (or close to perfect) signal reconstruction from the captured signal samples. Another interesting approach to sampling is event triggered sampling (ETS) [5,6]. In ETS schemes, a sample is taken when a certain pre-set event occurs in the signal. Choosing events skillfully can provide samples for good signal reconstruction (for certain specific class of signals [7–9]), or certain information estimation (example, see [10]). In this paper, we show the benefit of specific signal samples captured using ETS for analysis of oscillatory non-stationary signals. We model an oscillatory non-stationary signal with a time-varying sinusoid, and examine ETS for instantaneous amplitude (IA) and instantaneous frequency (IF) estimation. The goal is not signal reconstruction but efficient IA and IF estimation using the ETS scheme. We provide an algorithm for estimation with samples captured using a chosen event in an ETS.

We have shown earlier (in [9]) the sampling and reconstruction of sparse trigonometric polynomials using the ETS schemes, such as level crossings (LCs), and extrema

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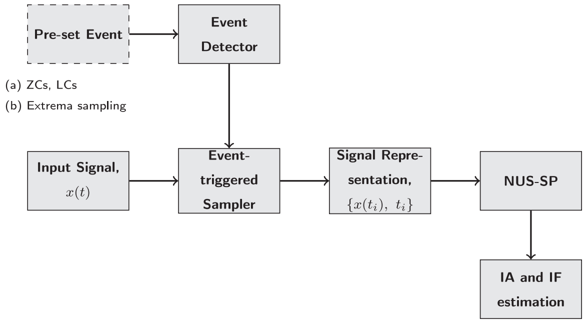

Fig. 1. An ETS and processing (NUS-SP stands for Non-Uniform Samples-Signal Processing) approach.

sampling (the circuit level implementation for detection of these events can be realized using low power circuit elements such as comparators for LC detection and ZC detection on the derivative of the signal for extrema detection [11]). The constituent elements in a trigonometric polynomial are time-invariant sinusoids; instead, we consider here analysis of a time-varying sinusoid using the same ETS schemes. This is to address suitability of ETS to analyze a wider class of signals which are non-stationary. We consider sinusoids evolving in amplitude and/or frequency along time.

A generic block diagram of ETS is shown in Fig. 1.

1.1. Why ETS for time-varying sinusoid analysis

Time-varying sinusoids are also referred as mono-component amplitude modulated (AM)–frequency modulated (FM) signals. The AM, in practice also referred as envelope, is equivalent to the IA, and FM is equivalent to the IF [12]. We will use IA and envelope terms interchangeably. An additive linear mixture model of time-varying sinusoids serves as a multi-component AM–FM signal model. Such a model has been extensively used in analysis of non-stationary signals (example, speech [13], music [14], natural sonar signals [15], birds songs [16], and surface gravity waves [17]). The underlying assumption is that each of the mono-component AM–FM signal in the mixture model tries to extract the information centered around certain carrier frequency. The signal analysis is thus performed by obtaining the IA and IF estimates of each mono-component AM–FM signal. Hence, it is highly desired that the IA and IF estimates, or the information signals, of each mono-component be obtained to utmost accuracy and robustness.

In conventional analogue signal processing (example, in radio communications), the IA and IF estimates are obtained using peak detector for IA, and ratio detector for IF [12]. However, with the advent of DSP and the applicability of AM–FM model to analysis of plethora of oscillatory non-stationary signals (much below the radio frequencies), the IA and IF estimates are obtained from the data-set captured using uniform sampling. The uniform sampling is at a rate much higher than the Nyquist-rate owing to the fact that an AM–FM signal is, in general, not bandlimited. This is our motivation to look out for a different sampling scheme which can adapt to the amplitude and frequency variations in the signal. The ETS schemes provide a good alternative in this regard since the average sampling rate is governed by instantaneous rate of occurrence of the pre-set event in the signal. Further, the widely used IA and IF estimation approaches using uniformly time sampled data-sets are discrete implementation of analytic signal approach devised by Gabor [18], and the discrete energy separation approach (DESA) [19,20]. These approaches, though serve the same purpose of IA and IF estimation, surprisingly operate on two different premises. The analytic approach operates using a global operation on the signal samples (convolution with a $1/t$ decaying Hilbert transform kernel), whereas the DESA approach uses a local operation of signal derivatives obtained with finite-order differences on the signal samples. The resulting implications are reviewed in [21,20], and also in practice the estimation performance degrades with noise. This is our motivation to look out for samples which are robust to in-band additive noise (than equi-spaced time samples captured in uniform sampling), and also aid in robust IA and IF estimation. We show that non-uniform samples captured using extrema sampling, with extrema as events in an ETS, are robust to additive in-band Gaussian noise and to jitter in detection instants. Making use of extrema as events in an ETS, we analyze IA and IF estimation, and design an estimation algorithm based on local polynomial regression (LPR) [22]. The order of the polynomial, and the number of samples chosen for LPR, provides local or global operation flexibility, and also adds noise robustness to the estimation.

1.2. Intuition

An intuitive data useful in IF estimation is zero-crossing (ZC) intervals [23]. In fact, to overcome the inadequacies of analytic signal approach, ZC intervals were used in [24] to decipher the IF glides in auditory nerve fibers. But this intuitive approach in [24], which although showed improved estimation, was overshadowed by auditory related findings presented therein. Drawn with further insights, work in [25] showed use of ZC instants, instead of intervals, data-set for precise IF estimation of phase signals. In [26], making use of slow varying instantaneous phase (IP) information, an LPR approach (referred as ZC-based) was proposed for arbitrary IF estimation. However, ZC instants do not encode amplitude information (assuming positive envelope [27]), and hence do not aid in envelope estimation. Extrema samples of an oscillatory nonstationary signal encode both IA and IF information. However, IA and IF information are intertwined at extrema. We analyze this, and state the conditions under which the information can be untwined, and hence ease estimation of IA and IF. The estimation performance is shown as an improvement over the analytic signal approach, DESA, and ZC-based approach under the stated conditions.

1.3. Paper contributions

- Analysis of ETS, with LC and extrema events, for additive in-band Gaussian noise, jitter in the sampling instants, and suitability for IA and IF estimation (Section 2).