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On the cyclostationary statistics of ultra-wideband signals in the presence of timing and frequency jitter

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Abstract

Cyclostationarity is an inherent characteristic of many man-made communication signals, which, if properly recognized, can be exploited for performing various signal-processing tasks. Determining the cyclostationary characteristics of a signal of interest is the first step in the design of signal processing systems exploiting this cyclostationary behaviour. This paper investigates the cyclostationary statistics of various signalling schemes employed in ultra-wideband (UWB) communication systems. Analytical expressions are derived for the cyclic autocorrelation and spectral correlation density functions in the presence of random timing and frequency jitter, which are characterized by discrete-time stationary random processes with known distribution functions.

Keywords: Ultra-wideband; Cyclostationarity; Spectral correlation; Jitter

1. Introduction

Ultra-wideband (UWB) radio is an emerging technology, which has been drawing a considerable amount of interest for military and commercial applications in the recent years due to the unique features it offers. The term UWB characterizes transmission systems with instantaneous spectral occupancy in excess of 500 MHz or a fractional bandwidth of more than 20% [1]. Such systems utilize a plethora of different techniques to spread the total transmit power over a considerably large bandwidth in the order of several GHz, which results in an extremely low-power spectral density. For commercial communication systems, this low spectral content allows the UWB technology to overlay already existing wireless communication systems with a negligible amount of interference, opening a huge swath of bandwidth to short-range low-power wireless applications without any licensing requirement [2]. On the other hand, UWB offers an inherent covertness with low probability of detection and interception (LPD/LPI) capabilities and a robustness to jamming, which is invaluable for military applications.

During the past several years, different signalling methods have emerged for UWB communications. In the early years of development of UWB technology, signalling schemes based on nanosecond baseband pulses were almost exclusively adopted, whereas the pulse-position modulation (PPM) has emerged as the most widely used modulation type, and time hopping (TH) as the predominant multi user access method. With the advance of technology, pulse amplitude modulation (PAM) and direct-spread code division multiple access (DS-CDMA) have become viable alternatives to the TH-PPM-based UWB systems.

Recently, largely as a consequence of the FCC regulations concerning the unlicensed use of $3.1-10.6$ GHz range for UWB systems, multicarrier UWB has attracted much attention, especially the multiband OFDM, which employs a combination of the conventional OFDM with frequency

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hopping. Compared to the pulse-based UWB, multiband OFDM technology offers a significantly higher degree of flexibility in terms of spectrum occupation and can make use of the FCC mask in a more efficient manner.

Due to the highly periodic structure underlying their generating mechanisms, both pulse-based and multicarrier UWB signals exhibit a high degree of cyclostationarity. The spectral correlation associated with this cyclostationary behaviour can be exploited to perform various signal-processing tasks including timing and channel estimation, equalization and presence detection of UWB signals buried in noise [3]. In [4], Gardner has introduced the cyclic autocorrelation and spectral correlation density functions that characterize cyclostationary random processes. The spectral correlation density function (SCD), which is the Fourier transform of the cyclic autocorrelation function (CAF) provides a measure of temporal correlation between spectral components of a cyclostationary process and can be regarded as a generalization to the conventional power spectral density function (PSD). However, unlike the PSD, SCD preserves phase information, which is much useful for various estimation problems. Determining analytical expressions of the CAF and SCD functions of a signal of interest is often necessary in the design of signal-processing systems exploiting cyclostationarity.

Even though the PSD of pulse-based UWB signals has been investigated thoroughly in the literature [5,6], no work has been reported on the CAF and SCD functions of signalling schemes employed in UWB. The primary objective of the following paper is to derive expressions for the cyclic autocorrelation and spectral correlation density functions for most commonly used pulse-based and multicarrier UWB signal structures. Since the effects of the implementing imperfections in the signal generation on the cyclostationary statistics of the signal are also of practical interest, the analysis in this work considers the presence of two common types of nonidealities in the signal of interest, i.e. random timing and frequency jitter, both of which are modelled as discrete-time stationary random processes with known statistical properties.

This paper is organized as follows: Section 2 presents a brief overview on the concept of cyclostationarity and provides the mathematical preliminaries. Section 3 investigates the cyclostationary characteristics of two basic types of pulse-based UWB signals in presence of random-timing jitter: TH-PPM and DS-CDMA UWB. In Section 4, the cyclostationary statistics of multiband OFDM UWB signals in presence of random timing and frequency jitter are derived. Finally, Section 5 summarizes the work.

2. Cyclostationarity: Preliminaries

This section provides a short review on the fundamental concepts and definitions of cyclostationarity and spectral correlation. For a thorough tutorial, the reader is referred to [3].

A zero-mean complex wide sense cyclostationary process $x(t)$ is characterized by a time-varying autocorrelation function (TVAF) $R_{xx}(t,\tau) = E\{x(t+\tau/2)x^*(t-\tau/2)\}$, which is periodic in time t with a fundamental period T_0 and can be represented as a Fourier series

$$R_{xx}(t,\tau) = \sum_{\alpha} R_{xx}^{\alpha}(\tau)\mathrm{e}^{\mathrm{j}2\pi\alpha t}, \tag{1}$$

where the sum is taken over integer multiples of fundamental cycle frequencies $\alpha = k\alpha_0 = k/T_0, k = 0, \pm 1, \pm 2, \ldots$. The Fourier coefficients, depending on the lag parameter τ can be calculated as

$$R_{xx}^{\alpha}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_{-T/2}^{T/2} R_{xx}(t,\tau)\mathrm{e}^{-\mathrm{j}2\pi\alpha t}\,\mathrm{d}t. \tag{2}$$

$R_{xx}^{\alpha}(\tau)$ is called the CAF and can be interpreted as a cross-correlation function between the frequency-shifted versions of the signal $x(t)$ by $\pm\alpha/2$ [4]. The spectral correlation density function $S_{xx}^{\alpha}(f)$ is defined as the Fourier transform of $R_{xx}^{\alpha}(\tau)$

$$S_{xx}^{\alpha}(f) = \int_{-\infty}^{\infty} R_{xx}^{\alpha}(\tau)\mathrm{e}^{-\mathrm{j}2\pi f\tau}\,\mathrm{d}\tau \tag{3}$$

and can be seen as a generalization of the conventional power spectral density function. $S_{xx}^{\alpha}(f)$ characterizes the temporal correlation between spectral components located at $f \pm \alpha/2$ and converges to the conventional power spectral density function for $\alpha = 0$.

$R_{xx}^{\alpha}(\tau)$ and $S_{xx}^{\alpha}(f)$ are discrete functions of the cycle frequency parameter α and are continuous in the lag parameter τ and frequency parameter *f*, respectively. For a non-cyclostationary process, $R_{xx}^{\alpha}(\tau) = 0$ and $S_{xx}^{\alpha}(f) = 0$ $\forall\alpha \neq 0$. Any nonzero value of the cycle frequency parameter α, for which $R_{xx}^{\alpha}(\tau) \neq 0$ or $S_{xx}^{\alpha}(f) \neq 0$ is called a *cycle frequency*, and the discrete set of the cycle frequencies $\mathbb{A}_{xx}$ is referred to as the *cycle spectrum*. A signal is said to exhibit cyclostationarity with the cycle frequency α_k, if $\alpha_k \in \mathbb{A}_{xx}$. For a random process with a TVAF that contains multiple incommensurate periodicities, the cycle spectrum contains the harmonics of each fundamental cycle frequency.

Virtually, all man-made communication signals exhibit cyclostationarity with cycle frequencies related to hidden periodicities underlying the signal and other related parameters, such as the modulation index, carrier frequency, symbol and/or chip rate, frequency hopping rate, period of the spreading or scrambling codes, etc. The existence of correlation between spectral components of cyclostationary signals may be considered as a spectral redundancy in the information theoretic sense, that can be exploited for various signal-processing applications in wireless communications, such as estimation of signal parameters, equalisation, channel estimation, direction of arrival estimation, spatial