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Single channel source separation and parameter estimation of multi-component PRBCPM-SFM signal based on generalized period ☆

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A B S T R A C T

This paper proposes an approach of single channel source separation and parameter estimation of multi-component PRBCPM-SFM (pseudo-random binary code phase modulated sinusoidal frequency modulation) signal. By transforming all components to SFM signals through square calculation, we may then apply singular value decomposition to determine the generalized period and the modulation frequency of the SFM signal. The modulation index and carrier frequency are determined by searching for discrete points and optimizing calculations. The initial phase can be determined by calculating the inner product. Finally, given that the pseudo-random binary code is a real signal, the PN (Pseudo-noise) sequence and the amplitude can be estimated. Our proposed method can estimate the *SNR* by using the method of subspace-based decomposition, and the estimated *SNR* can be used to adaptively stop separation. Experimental results demonstrate the algorithm's performance.

1. Introduction

As a typical low probability of intercept (LPI) radar signal, the pseudo-random binary code phase modulated sine frequency modulation (PRBCPM-SFM) signal combines the advantages of the pseudo-random signal and the sine signal. Because of its good range resolution, speed resolution and anti-jamming performance, it has been used widely in radar and micro-detector systems. For such systems, the extraction of characteristic parameters is a significant problem, and many solutions have been proposed.

At present, there are several methods used to estimate PRBCPM-SFM signal parameters, such as spectral correlation [1–5], periodic ambiguity function [6,7], wavelets [8–10] and time–frequency distribution [11–13]. Extraction of mono-component PRBCPM-SFM signal parameters by using these methods yields satisfying results. Yet, in battlefield environments, where channel resources are limited, this makes it difficult to achieve good results when using the above methods to analyze multi-component mixed PRBCPM-SFM signals over a single channel.

Because of the complex time–frequency distribution, most existing single channel source separation methods aimed at speech signals cannot be used to separate a multi-component radar signal. Effective methods are based on the modulation structure of the radar signal; for example, the fractional Fourier transform [14–16] might be used to detect a multi-component LFM signal and extract modulation information. Liu [17] used an energy operator to estimate the modulation information of a multi-component radar signal. Adaptive chirplet-based decomposition [18–20] is an effective means that may be used to separate multi-component frequency modulation signals. Although these methods can separate multi-component frequency modulation radar signals, they cannot be used to separate multi-component PN sequence modulated signals (such as a PRBCPM-SFM signal).

This paper proposes an effective method of source separation and parameter estimation for multi-component PRBCPM-SFM signals.

2. Multi-component PRBCPM-SFM signal in single channel

First, we express the mathematic models of a multi-component PRBCPM-SFM signal, and then we analyze it squared.

2.1. Multi-component signal with noise

In PRBCPM-SFM radar, the intercepted multiple-component mixed signal with noise can be written as [11,12]:

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$$x(t)=s(t)+v(t)=\sum_{i=1}^{K}s_i(t)+v(t)$$
$$=\sum_{i=1}^{K}A_i\cdot U_i(t)\cdot e^{j\theta_i(t)}+v(t)$$
$$=\sum_{i=1}^{K}A_i\cdot U_i(t)$$
$$\cdot\exp\{j\cdot[2\pi(f_{0i}t+m_{fi}\cdot\cos(2\pi f_{mi}t))+\theta_{0i}]\}+v(t) \quad (1)$$

where $v(t)$ is the complex additive white Gaussian noise with zero mean and variance σ^2 and $s(t)$ is the intercepted multiple-component PRBCPM-SFM signal. The number of components is K. For the ith component $s_i(t)$, A_i is the amplitude, where $A_i>0$ $(i=1,2,\cdots,K)$ and $A_1>A_2>\cdots>A_K$. $\theta_i(t)$ is the phase expression, f_{0i} is the carrier frequency, Δf_i is the maximum frequency offset, $m_{fi}=\frac{\Delta f_i}{f_{mi}}$ is the modulation index, f_{mi} is the modulation frequency, and θ_{0i} is the initial phase. The expression of a PN sequence (in fact, the Pseudo Random Binary Code) $U_i(t)$ [11,12] is:

$$U_i(t)=\sum_{k=0}^{\infty}\sum_{p=0}^{P_i-1}c_{ip}\,rect\left(\frac{t-T_{ci}/2-pT_{ci}-kP_iT_{ci}}{T_{ci}}\right) \quad (2)$$

where $rect(\frac{t}{T_{ci}})=\begin{cases}1, & |t|\le T_{ci}/2\\ 0, & \text{otherwise}\end{cases}$, P_i and T_{ci} are the PN sequence length and symbol width. c_{ip} is the sequence with the value $+1$ or -1, and c_{ip} can also be regarded as phase mutation $c_{ip}=\{e^{j0},e^{j\pi}\}$. Obviously, $U_i(t)$ is periodic with period P_iT_{ci}, and in general we set $P_iT_{ci}=1/f_{mi}$.

The discrete form of Eq. (1) is represented as:

$$x[n]=x(n\cdot T_s) \quad (3)$$

where T_s is the sampling period. In this paper, the discrete form is represented by $[n]$, and the continuous form is represented by (t).

2.2. Square calculation of a multi-component signal

From Eq. (1), we may transform all components into SFM signals through a square calculation, and the process is given by Eq. (4).

$$\tilde{x}[n]=\{x[n]\}^2$$
$$=\left\{\sum_{i=1}^{K}s_i[n]+v[n]\right\}^2=\left\{\sum_{i=1}^{K}A_i\cdot U_i[n]\cdot e^{j\theta_i[n]}+v[n]\right\}^2$$
$$=\sum_{i=1}^{K}A_i^2\cdot U_i^2[n]\cdot e^{j2\theta_i[n]}$$
$$+2\sum_{i=1}^{K}\sum_{\substack{k=1\\k\neq i}}^{K}A_i\cdot A_k\cdot U_i[n]\cdot U_k[n]\cdot e^{j\theta_i[n]}\cdot e^{j\theta_k[n]}$$
$$+2v[n]\cdot\sum_{i=1}^{K}A_i\cdot U_i[n]\cdot e^{j\theta_i[n]}+v^2[n]$$
$$=\tilde{s}[n]+\tilde{h}[n]+\tilde{v}[n] \quad (4)$$

Since $\tilde{s}[n]=\sum_{i=1}^{K}A_i^2\cdot U_i^2[n]\cdot e^{j2\theta_i[n]}$, $U_i^2[n]=1$, we see that

$$\tilde{s}[n]=\sum_{i=1}^{K}A_i^2\cdot e^{j2\theta_i[n]}=\sum_{i=1}^{K}\tilde{s}_i[n]$$
$$=\sum_{i=1}^{K}A_i^2\cdot\exp\{j\cdot[2\pi(2f_{0i}n\cdot T_s+2m_{fi}\cdot\cos(2\pi f_{mi}n\cdot T_s))$$
$$+2\theta_{0i}]\} \quad (5)$$

Eq. (5) transforms all components into SFM signals $\tilde{s}_i[n]=A_i^2\cdot e^{j2\theta_i[n]}$.

For $\tilde{h}[n]=2\sum_{i=1}^{K}\sum_{\substack{k=1\\k\neq i}}^{K}A_i\cdot A_k\cdot U_i[n]\cdot U_k[n]\cdot e^{j\theta_i[n]}\cdot e^{j\theta_k[n]}$, it is still multiplied by the PN sequence $U_i[n]\cdot U_k[n]$. In this paper, for the squared signal, we estimate the parameters using the method based on the characteristics of frequency variance of the SFM signal, as shown in Sections 4.1–4.4. However, $\tilde{h}[n]$ and $\tilde{v}[n]$ do not show the properties of the SFM signal, they would not affect the estimation performance significantly, therefore, here we regard $w[n]=\tilde{h}[n]+\tilde{v}[n]$ as a new noise component. We rewrite $\tilde{x}[n]$ as:

$$\tilde{x}[n]=\tilde{s}[n]+w[n]=\sum_{i=1}^{K}\tilde{s}_i[n]+w[n]=\sum_{i=1}^{K}A_i^2\cdot e^{j2\theta_i[n]}+w[n] \quad (6)$$

In Eq. (6), there are K SFM components in the squared multi-component signal.

3. Generalized period

We transformed all the components into SFM signals, in order to estimate all the parameters, here we introduce the property of the generalized period of the SFM signal.

3.1. The property of the generalized period

A standard periodic signal $s[n]$ satisfies the following equation:

$$s[n+kN]=s[n],\quad n\in[1,N],\ k\ge 0,\ k\in Z \quad (7)$$

where N is the period.

In practical applications, there is a kind of signal that does not satisfy equation (7), but rather satisfies this equation:

$$s[n+kN]=e^{jk\cdot\Delta\theta}\cdot s[n],\quad n\in[1,N],\ k\ge 0,\ k\in Z \quad (8)$$

where $\Delta\theta$ is a constant. A signal satisfying Eq. (7) also satisfies Eq. (8) when $\Delta\theta=0$.

Non-standard periodic signals that satisfy Eq. (8) when $\Delta\theta\neq 0$ are called generalized periodic signals, and the generalized period is N.

3.2. Generalized period of an SFM signal

An SFM component of $\tilde{x}[n]$ in Eq. (6) can be expressed as:

$$\tilde{s}_i[n]=A_i^2\cdot e^{j2\theta_i[n]}$$
$$=A_i^2\cdot\exp\{j\cdot[2\pi(2f_{0i}n\cdot T_s+2m_{fi}$$
$$\cdot\cos(2\pi f_{mi}n\cdot T_s))+2\theta_{0i}]\}$$
$$=A_i^2\cdot\exp\left\{j\cdot\left[2\pi\left(2f_{0i}\frac{n}{F_s}+2m_{fi}\right.\right.\right.$$
$$\left.\left.\left.\cdot\cos\left(2\pi f_{mi}\frac{n}{F_s}\right)\right)+2\theta_{0i}\right]\right\} \quad (9)$$

where F_s is the sampling frequency, and T_s is the sampling period. Let $N_{mi}=\frac{F_s}{f_{mi}}$, and with two positive integers p and q, we have: