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Adaptive Separation of Subcarrier for Wireless Link of Satellite Communication

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Abstract Currently, the subcarrier on the satellite communication wireless link has uncertain signal number and bandwidth and non-overlapped frequency spectra of mixed signals, and thus can hardly be separated and identified. Through analysis, a simple and effective estimation algorithm for subcarrier frequency was proposed and the code rate was estimated based on the instantaneous characteristics of the modulated signal. Results show that, using the proposed adaptive separation and recognition method, multiple signals can be effectively separated from the mixed signal, with high precision and strong noise immunity. Moreover, after partition, each subcarrier can be separated by the filter for modulation. The method is characterized by simple principle and ease of implementation.

Keywords Satellite communication · Subcarrier · Separation

1 Introductions

Currently, multiple communication signals in a frequency band can be detected mainly in two ways—manual method and electric scanning [1, 2]. Using the former method, the signals are separated through manually tuning and filtering based on the observations of the distribution of frequency spectrum. Manual method prevails in practical applications owing to its low miss and false detection rates; however, it is always slow, inefficient and labor-intensive [3, 4]. Electric scanning method is to analyze the signal' spectral characteristics using the computer and perform automatic detection and separation on the mixed signals using certain algorithms [5, 6]. This method generally exhibits high miss and false detection rates. Using electric scanning, the condition should be investigated–the mixed signals including a certain number of unknown signals that are mutually independent.

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Considering that both the signal source and transmission characteristics are unknown, some scholars proposed to use antenna array receiving system and spatial filtering and then achieved the separation of multiple signals using blind separation algorithm based on the difference among the received signals. Such kind of problems, also known as blind source separation [7–9], now have been extensive investigated. However, there still lacks of favorable detection and separation methods for the mixed signals in which the number of the mutually independent signals is unknown and the signal bandwidth is uncertain [10, 11].

This article focused on the separation of the signals with uncertain signal number, bandwidth and separable frequency spectra and proposed an adaptive separation algorithm by combining wavelet multi-resolution analysis and Fourier transform. This algorithm can quickly and accurately separate the components from the mixed signal. Then, the separated signals were identified using the estimation of subcarrier frequency and code rate.

2 Estimation of Signal Frequency Spectrum Based on Fast Fourier Transform (FFT)

For the signal to be separated $s(t)$ in which the frequency spectra of each mixed signals do not overlap mutually, fast Fourier transformation (FFT) is applicable for spectral analysis. Given a observed signal sequence $s(n)$, FFT at Point M can be written as:

$$s(k) = \sum_{n=0}^{M-1} s(n)e^{-j2\pi k/M}(0 \le k \le M - 1) \tag{1}$$

Then, the power spectral density (PSD) of s(n) can be calculated by:

$$p(k) = s(k) \times \overline{s(k)}, (0 \le k \le M - 1) \tag{2}$$

where the symbol of '$-$' represents the complex conjugate operation.

(1) Coarse signal separation

If $P(i)$ satisfies $P(i) < P(i-1)$, $P(i) < P(i+1)$ and $P(i) < \delta_1$ (where δ_1 denotes the threshold of the amplitude of the power spectrum for judging whether i is the demarcation point of the frequency spectrum), the frequency point i can be regarded as the demarcation point of the frequency spectra of two mixed signals.

The reason for the setting of $P(i) < \delta_1$ in coarse signal separation is that a bifurcation would occur in the frequency spectrum of FSK modulated signal during communication. To prevent the bifurcate frequency spectrum of FSK modulated signal from being separated into two signal frequency spectra, the amplitude of the frequency spectrum at the demarcation point i should be judged.

Then, the received communication signals were coarsely separated, and the set of the frequency demarcation points of the mixed signals $FP = \{i_1, i_2, \ldots, i_N\}$ was acquired, in which the frequency band between two adjacent frequency demarcation points was the frequency band where the mixed signal was located. Since the noise existed in the receiving environment of communication signal, the power spectrum between two adjacent frequency demarcation points in coarse signal separation may also be produced by the noise. It is necessary to screen the frequency boundary points after coarse separation, and thus the following fine signal separation was designed.

(2) Fine signal separation

If $\max\{P(i), P(i+1), \ldots, P(j)\} > \delta_2$ (where $i,j \in FP = \{i_1, i_2, \ldots, i_N\}$, the frequency points i and j are any two adjacent frequency boundary points in the set $FP = \{i_1, i_2, \ldots, i_N\}$ and δ_2 is the judgment threshold of the peak of the power spectrum between i and j), the frequency spectrum between two frequency boundary points i and j can be regarded as the frequency spectrum of a mixed signal in blind communication.

At a certain signal-to-noise ratio (SNR), the peak of the power spectrum of interference noise was generally lower than that of the signal. Therefore, an appropriate threshold was set for judging whether the power spectrum between two adjacent frequency boundary points was the power spectrum of a mixed signal.

Overall, signal separation algorithm includes two steps, in which the selection of the threshold values, δ_1 and δ_2, are of crucial importance. Too large δ_1 can easily lead to the dividing of the frequency spectrum of a signal into the frequency spectra of two signals in coarse separation, such as the bifurcate frequency spectrum of FSK modulated signal; by contrast, if a too small δ_1 is used, the boundary points of the frequency spectra of two signals can be easily regarded as a bifurcate frequency point of a signal for processing, i.e., the frequency spectra of two signals can hardly be separated. For δ_2, if the preset value is too large, the frequency spectrum of a signal in a certain frequency band may be processed as the frequency spectrum of noise, leading to the loss of signal; if the preset value is too small, the frequency spectrum of noise in a certain frequency band may be mistaken as the frequency spectrum of a certain signal, i.e., the separated signals are poor in reliability.

Under different conditions, the mixed signals in blind communication are generally composed of different signals and located in different bands, with different peaks and amplitudes of the bifurcation points of frequency spectra. Accordingly, the thresholds, δ_1 and δ_2, were not constant for effectively separating the mixed signals in blind communication under different conditions. Therefore, it is crucial to design an algorithm that can adaptively determine the values of δ_1 and δ_2 in accordance with the actual situation of the received blind communication signal.

3 Adaptive Separation Process

According to the suggestions of the Consultative Committee for Space Data System (CCSDS), the sine wave should be used as the subcarrier, with the modulation mode of FSK or PSK. In the unified S-band (USB) system, the subcarrier should be added to the ranging signal and then modulated to the carrier. Generally, the sidetone ranging signal is set as 100 kHz, the telecommand subcarrier is set as 8 or 16 kHz, and the subcarrier is set within the range of 20–100 kHz or above 100 kHz so as to avoid the sidetone signal. The channel number of subcarrier should be determined in accordance with the type of baseband signal. For example, in order to acquire all the parameters regarding the running times of medium-earth-orbit (MEO) or low-earth-orbit satellites, the real-time and delay encoding systems are generally set, which can be distinguished from each other with the use of two subcarriers. In the present study, the zero-point-based partition method was proposed to determine the number of subcarriers and them conduct the partition.

For the PSK modulated signal, the frequency spectrum (only considering the positive frequency) is a single-peak continuous spectrum with the carrier frequency as the center; for the FSK modulated signal, the frequency spectrum varies with the modulation index *h*. Assuming that the two frequencies of FSK are denoted as f1 and f2 and the bit rate is Rs, the modulation index h can be calculated by $h = |f_2 - f_1|/Rs$. The effects of the variation of h on the partition of subcarriers will be discussed later.

The procedures of the proposed adaptive separation algorithm was designed below.

Step 1 Conduct FFT on the blind communication signal $s(t)$ and calculate the power spectrum of $s(t)$, denoted as $P_s(\omega)$.

Step 2 Conduct discrete orthogonal wavelet transform (DWT) on $P_s(\omega)$ based on wavelet multi-resolution analysis and obtain the coarse approximation of $P_s(\omega)$ on a certain decomposition level i and the reconstructed signal, denoted as A_i and RA_i, respectively.

Step 3 Determine the number of the mixed signals in $s(t)$ based on A_i, denoted as N_0.

Step 4 Let the initial thresholds δ_1 and δ_2 equal to m, i.e., $\delta_1 = \mathrm{m}$ and $\delta_2 = \mathrm{m}$, where m denotes the mean value of $P_s(\omega)$, and then conduct blind channel separation on the reconstructed signal RA_i of $s(t)$ after coarse separation.

Step 5 Conduct adaptive adjustment on δ_1 and δ_2. The specific process is described below.

If $N > N_0$, $\delta_1^{'} = \delta_1 + \Delta\delta_1$ and $\delta_2^{'} = \delta_2 + \Delta\delta_2$;

If $N < N_0$, $\delta_1^{'} = \delta_1 - \Delta\delta_1^{'}$ and $\delta_2^{'} = \delta_2 - \Delta\delta_2^{'}$.where N denotes the number of separated channels; $\Delta\delta_1$, $\Delta\delta_1^{'}$, $\Delta\delta_2$ and $\Delta\delta_2^{'}$ are the corrected values of δ_1 and δ_2, respectively.

Step 6 Conduct the blind channel separation on the coarse-resolution approximation reconstructed signal RA_i of $s(t)$ using the corrected thresholds $\delta_1^{'}$ and $\delta_2^{'}$.

Step 7 If $N^{'} \neq N_0$ (where$N^{'}$ denotes the number of separated signals after blind channel separation using $\delta_1^{'}$ and $\delta_2^{'}$), return to Step 5 and repeat the operation until the number of blind channels equals to N_0, and meanwhile, acquire the power spectra of each blind channels separated from the power spectrum $P_s(\omega)$ and the starting and destination points in the frequency band.

Step 8 Design the corresponding filter and separate the mixed signals $s_1(t)$, $s_2(t)$, …, $s_N(t)$ from $s(t)$.

The simulations were performed in accordance with the above-described procedures. The corrected values of δ_1 were set as zero, i.e., $\Delta\delta_1 = 0$ and $\Delta\delta_1^{'} = 0$, and the corrected values of δ_2 were set as $0.01m$ and $0.005m$, respectively, i.e., $\Delta\delta_2 = 0.01m$ and

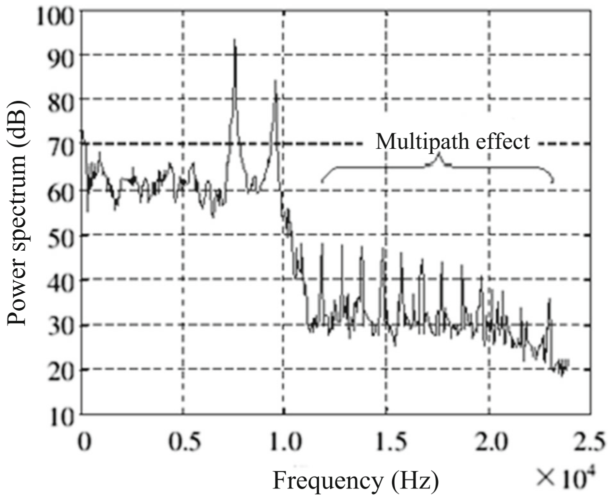

Fig. 1 Power spectrum $P_s(\omega)$ of $s(t)$

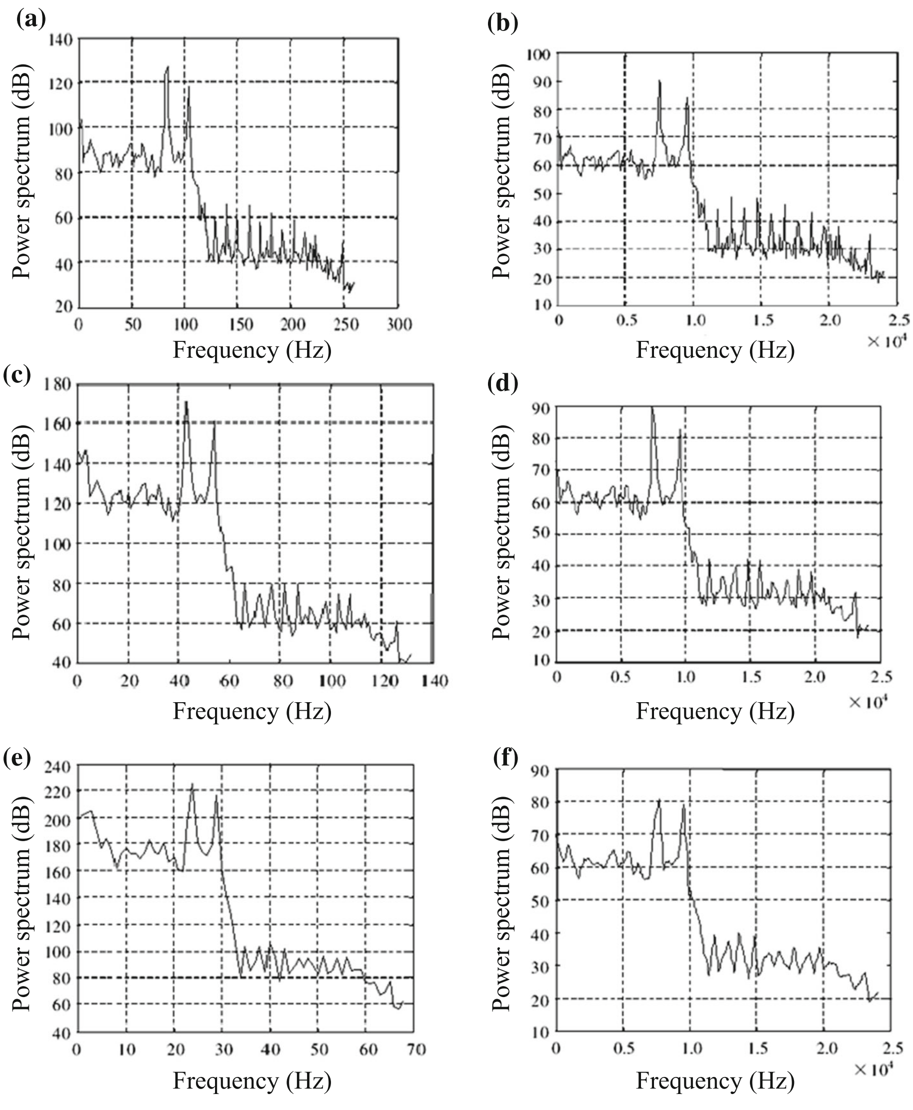

Fig. 2 Separation process of the subcarriers. **a** Coarse approximation of $P_s(\omega)$ for A_1, **b** Reconstructed signal RA_1, **c** Coarse approximation of $P_s(\omega)$ for A_2, **d** Reconstructed signal RA_2, **e** Coarse approximation of $P_s(\omega)$ for A_3, **f** Reconstructed signal RA_3

$\Delta\delta_2' = 0.005m$, where m denotes the mean value of $P_s(\omega)$. Figures 1 and 2 display the simulation results. Figure 3 shows the separation results of subcarriers.

According to the simulation results, the proposed fast blind channel separation algorithm can effectively separate the subcarriers from the mixed signals with a high precision.

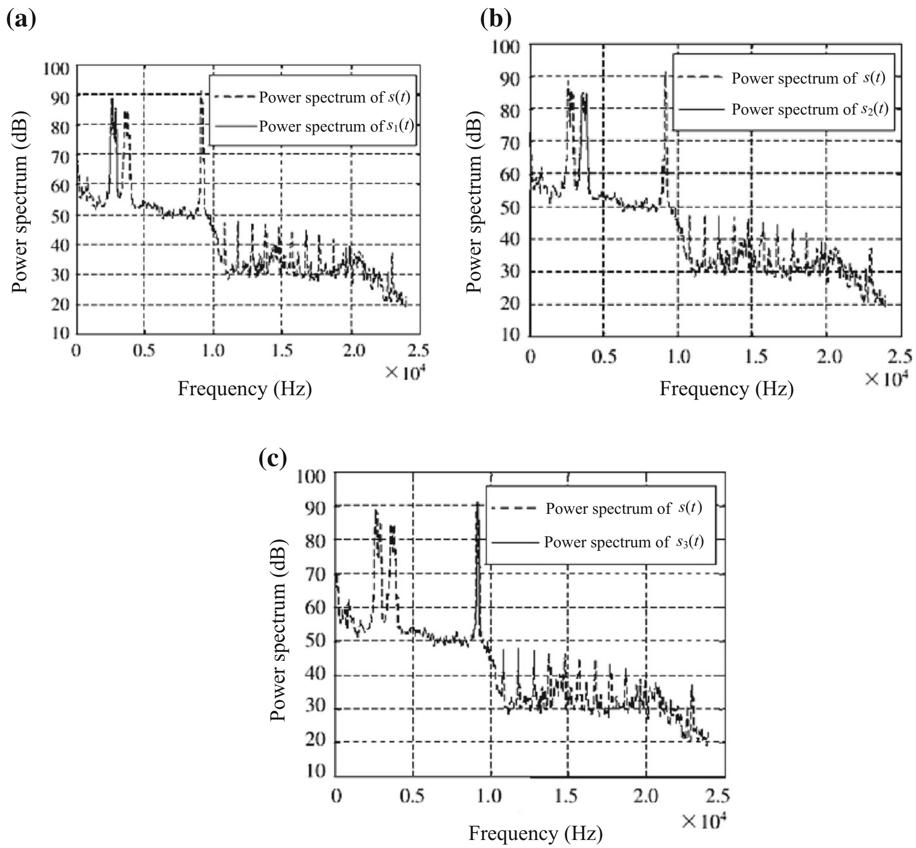

Fig. 3 Separation results of the subcarriers. **a** Signal $s_1(t)$ separation from source signal $s(t)$, **b** Signal $s_2(t)$ separation from source signal $s(t)$, **c** Signal $s_3(t)$ separation from source signal $s(t)$

4 Conclusions

This article combined wavelet multi-resolution analysis and Fourier transform and proposed an adaptive separation algorithm for subcarrier signals with uncertain signal number and bandwidth and non-overlapped frequency spectra of mixed signals. Through analysis, a simple and effective estimation algorithm for subcarrier frequency was proposed and the code rate was estimated based on the instantaneous characteristics of the modulated signal. Results show that, using the proposed adaptive separation and recognition method, multiple signals can be effectively separated from the mixed signal, with high precision and strong noise immunity. Moreover, after partition, each subcarrier can be separated by the filter for modulation. The method is characterized by simple principle and ease of implementation.

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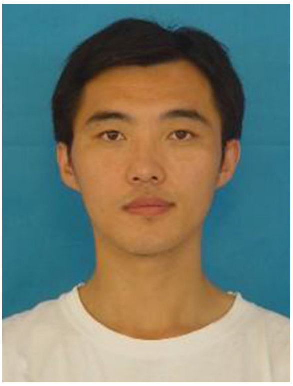

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