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New Blind Recognition Method of SCLD and OFDM in Alpha-Stable Noise

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Abstract

This paper deals with modulation classification under the alpha-stable noise condition. Our goal is to discriminate orthogonal frequency division multiplexing (OFDM) modulation type from single carrier linear digital (SCLD) modulations in this scenario. Based on the new results concerning the generalized cyclostationarity of these signals in alpha-stable noise which are presented in this paper, we construct new modulation classification features without any priori information of carrier frequency and timing offset of the received signals, and use support vector machine (SVM) as classifier to discriminate OFDM from SCLD. Simulation results show that the recognition accuracy of the proposed algorithm can be up to 95% when the mix signal to noise ratio (MSNR) is up to −1 dB.

Keywords

Modulation Recognition, Generalized Second-Order Cyclic Statistics, OFDM, Alpha-Stable Noise

1. Introduction

With wide application of OFDM, the recognition of OFDM signal has become a hot issue in various fields of applications among cognitive radio and military applications. Algorithms for the recognition of OFDM versus SCLD signals in AWGN scenario have been reported in [1]-[6]. The algorithm proposed in [1] is based on the signal empirical distribution function to recognize OFDM. Fourth- and sixth-order signal moments are employed in [2] to identify OFDM and single-carrier. Wavelet analysis is also employed to distinguish OFDM and SCLD in [3] [4]. The algorithm proposed is based on the second-order cyclic cumulate to recognize OFDM versus SCLD signals under time dispersive channel in [5]. Based on the spectrum analysis, an algorithm was proposed to recognize OFDM in [6]. The above results were developed under the simplified assumption of ad-

ditive white Gaussian noise channel. But, many noise processes are impulsive in nature. Impulsive channels have been arisen in underwater (ice-cracks), atmospheric (thunderstorms) environments, and other mobile communication problems [7]. Impulsive noise can be modelled as alpha-stable distribution process which is different from Gaussian noise. When the communication channel in nature is impulsive channel modelled as alpha-stable distribution process, the existing recognition algorithms of OFDM versus SCLD would become invalid, because the impulsive noise does not have second-order and higher order statistics. For this reason, we study the recognition of OFDM against SCLD signals in alpha-stable noise here. In this paper, we extract new modulation classification features from the new results concerning the generalized cyclostationarity of OFDM and SCLD signals in alpha-stable noise, and use support vector machine (SVM) as classifier to these signals. The recognition algorithm avoids the need for timing and carrier recovery and the estimation of signal and noise powers. Simulation results show that the proposed method have good performances in alpha-stable noise.

The rest of the paper is organized as follows. The SCLD and OFDM signal models is presented in Sections 2, the proposed recognition algorithm is introduced in Section 3 and simulation results are discussed in Section 4. Finally, our conclusions are presented in Section 5.

2. Signal Models

The received signal can be written as,

$$r(t) = s(t) + w(t) \tag{1}$$

where $s(t)$ means the transmitted signal, $w(t)$ is alpha-stable noise.

If the modulation type of the transmitted signal is OFDM, $s(t)$ can be represented by $s(t)_{OFDM}$, which is expressed as,

$$s(t)_{OFDM} = Ae^{j\theta} e^{j2\pi\Delta f_c t} \sum_{k=0}^{K-1} \sum_{l=-\infty}^{\infty} a_{k,l} e^{j2\pi k\Delta f_k (t-lT_s - \mu T_s)} \\ \times g(t - lT_s - \mu T_s) \tag{2}$$

where A is the amplitude, θ is the phase, Δf_c is the carrier frequency offset, $0 \leq \mu \leq 1$ is the timing offset, $g(t)$ is the overall impulse response of the transmit and receive filters, K is the number of subcarriers of the OFDM signal, $a_{k,l}$ is the symbol transmitted on the *k*th subcarrier over the *l*th symbol period, Δf_k is the frequency separation between two adjacent subcarriers, T_s is the OFDM symbol period, and $T_s = T_u + T_{cp}$. The data symbols $\{a_{k,l}\}$ are assumed to be zero-mean independent and identically distributed (i.i.d.) random variables, with values drawn either from a quadrature amplitude modulation (QAM) or phase shift keying (PSK) constellation.

If the modulation type of the transmitted signal is SCLD, $s(t)$ can be represented by $s(t)_{SCLD}$, which is expressed as,

$$s(t)_{SCLD} = Be^{j\theta} e^{j2\pi\Delta f_c t} \sum_{l=-\infty}^{\infty} b_l g(t - lT_c - \mu T_c) \tag{3}$$

where B is the amplitude, θ is the carrier phase, Δf_c is the frequency offset, T_c is the symbol period, $0 \leq \mu \leq 1$ is the timing offset, $g(t)$ is the overall impulse response of the transmit and receive filters, b_l is the symbol transmitted in the *l*th symbol period. The data symbols $\{b_l\}$ are assumed to be zero-mean independent and i.i.d., with values drawn either from a quadrature amplitude modulation (QAM) or phase shift keying (PSK) constellation.

The alpha-stable noise $w(t)$ is defined by its characteristic function, since a closed form expression for its probability density function (pdf) is not always available. The characteristic function $\phi(u)$ is given by [8],

$$\phi(u) = \exp\left(jau - \gamma |u|^{\alpha} \left[1 + j\beta \operatorname{sgn}(u)\omega(u,\alpha) \right] \right) \tag{4}$$

In (4), $\omega(u,\alpha)$ and $\operatorname{sgn}(u)$ is given as,

$$\omega(u,\alpha) = \begin{cases} \tan(\pi\alpha/2) & \alpha \neq 1 \\ (2/\pi)\log|u| & \alpha = 1 \end{cases} \tag{5}$$

and

$$\operatorname{sgn}(u) = \begin{cases} 1 & u > 0 \\ 0 & u = 0 \\ -1 & u < 0 \end{cases} \tag{6}$$

where α, γ, and a are the characteristic exponent, dispersion, and location, respectively. Without loss of generality, noise employs standard symmetric alpha-stable distribution-SαS as model. Because the SαS noise do not have finite second moment, its noise variance loses meaning. So a mixed signal to noise ratio-MSNR is employed, MSNR is given by [8],

$$MSNR = 10\lg(\sigma_s^2/\gamma) \tag{7}$$

where σ_s^2 represents the signal variance and γ is dispersion of alpha-stable noise.

3. The Recognition Algorithm of OFDM and SCLD in Alpha-Stable Distributed Noise

3.1. The Generalized Second-Order Cyclic Statistics of OFDM and SCLD

Alpha-stable noise does not have second-order and higher order statistics so that many traditional OFDM identification algorithms will be invalid. To solve the problem that traditional second-order cyclic statistics significantly degenerate in the alpha-stable noise, the concept of generalized second-order cyclic statistics was proposed in [9]. The core of the concept is by use of some kind of nonlinear transformation to suppress the pulse noise, and then process the transformed signal by traditional second-order cyclic statistical analysis. Taking advantages of the concept, a new method to recognize modulation type between OFDM and SCLD in this paper. Firstly, a nonlinear transformation function is defined as following to transform the received signal

$$f\left[r(t)\right] = \frac{1}{|r(t)|} r(t) \tag{8}$$

where $r(t)$ represents the received signal.

The autocorrelation function of signal $f\left[r(t)\right]$ can be expressed as,

$$
\begin{aligned}
G(t,\tau) &= E\left[f\left[r(t)\right]f^*\left[r(t+\tau)\right]\right] \\
&= E\left[\frac{s(t)s^*(t+\tau)}{|s(t)+w(t)||s(t+\tau)+w(t+\tau)|}\right. \\
&\quad \left. + \frac{w(t)w^*(t+\tau)}{|s(t)+w(t)||s(t+\tau)+w(t+\tau)|}\right]
\end{aligned}
\tag{9}
$$

When MSNR is higher enough, $|s(t)| \gg |w(t)|$, (9) can be approximated as,

$$
\begin{aligned}
G(t,\tau) &= E\left[f\left[r(t)\right]f^*\left[r(t+\tau)\right]\right] \\
&\approx E\left[\frac{s(t)s^*(t+\tau)}{|s(t)||s(t+\tau)|}\right] + E\left[\frac{w(t)w^*(t+\tau)}{|s(t)||s(t+\tau)|}\right] \\
&= G_s(t,\tau) + G_w(t,\tau)
\end{aligned}
\tag{10}
$$

where $G_s(t,\tau) = E\left[\dfrac{s(t)s^*(t+\tau)}{|s(t)||s(t+\tau)|}\right]$,

$G_w(t,\tau) = E\left[\dfrac{w(t)w^*(t+\tau)}{|s(t)||s(t+\tau)|}\right]$, $G_s(t,\tau)$ represents autocorrelation information

of $s(t)$. When $|s(t)| \gg |w(t)|$, the amplitude of noise is suppressed. Obviously, when processing the received signal $r(t)$ with nonlinear transformation, the unique features of signal $s(t)$ are maintained in $G_s(t,\tau)$, and the amplitude of noise is effectively limited. For the OFDM signal, (2) can be put into (10) and (10) becomes

$$
\begin{aligned}
G_{OFDM}(t,\tau) &= E\left[\frac{s(t)s^*(t+\tau)}{|s(t)|\cdot|s(t+\tau)|}\right] \\
&= E\left[\frac{e^{-j2\pi\Delta f_c\tau}\sum_{k=0}^{K-1}a_k(t)e^{j2\pi k\Delta f_k t}g(t)}{\left|\sum_{k=0}^{K-1}a_k(t)e^{j2\pi k\Delta f_k t}g(t)\right|}\right. \\
&\quad \left. \times \frac{\sum_{k=0}^{K-1}a_k^*(t+\tau)e^{-j2\pi k\Delta f_k(t+\tau)}g^*(t+\tau)}{\left|\sum_{k=0}^{K-1}a_k(t+\tau)e^{j2\pi k\Delta f_k(t+\tau)}g\ (t+\tau)\right|}\right] \otimes \sum_{l=-\infty}^{\infty}\delta(t-lT_s-\mu T_s) \\
&= E\left[\frac{e^{-j2\pi\Delta f_c\tau}\sum_{k=0}^{K-1}a_k(t)e^{j2\pi k\Delta f_k t}\sum_{k=0}^{K-1}a_k^*(t+\tau)e^{-j2\pi k\Delta f_k(t+\tau)}}{\left|\sum_{k=0}^{K-1}a_k(t)e^{j2\pi k\Delta f_k t}\right|\left|\sum_{k=0}^{K-1}a_k(t+\tau)e^{j2\pi k\Delta f_k(t+\tau)}\right|}\right] \\
&\quad \times P\left[g(t)\right]P\left[g^*(t+\tau)\right]\otimes\sum_{l=-\infty}^{\infty}\delta(t-lT_s-\mu T_s)
\end{aligned}
\tag{11}
$$

where $a_k(t)$ is the information data transmitted within the *k*th subcarrier, and

the data is assumed to be i.i.d.. Hence, (11) can be further re-written as,

$$G_{OFDM}(t,\tau) = E\left[\frac{s(t)s^*(t+\tau)}{|s(t)||s(t+\tau)|}\right]$$

$$= \left(e^{-j2\pi\Delta f_c\tau}\sum_{k=0}^{K-1}C_{k,s}(t)e^{-j2\pi k\Delta f_k\tau}P[g(t)]\right.$$

$$\left.\times P[g^*(t+\tau)]\right)\otimes\sum_{l=-\infty}^{\infty}\delta(t-lT_s-\mu T_s) \tag{12}$$

where $C_s(t) = E\left[\dfrac{a_k(t)a_k(t+\tau)}{\overline{s}(t)\overline{s}(t+\tau)}\right]\geq 0$,

$\overline{s}(t) = \left|\sum_{k=0}^{K-1}a_k(t)e^{j2\pi k\Delta f_k t}\right|$, $(\cdot)^*$ represents the complex conjugate, $P[\cdot]$ stand

for operator, which maintain the phase of signal, $\delta(\cdot)$ is the Dirac delta function and $\otimes$ is convolution. From (12) one can see that $G_{OFDM}(t,\tau)$ is a periodic function with fundamental periodic T_s. The autocorrelation function can be easily expressed as a Fourier series, and the Fourier transform of (12) yields

$$G_{OFDM}(\varepsilon,\tau) = \Im\{G_{OFDM}(t,\tau)\}$$

$$= \int_{-\infty}^{\infty}\left(e^{-j2\pi\Delta f_c\tau}\sum_{k=0}^{K-1}C_s(t)e^{-j2\pi k\Delta f_k\tau}P[g(t)]\right.$$

$$\left.\times P[g^*(t+\tau)]\right)\otimes\sum_{l=-\infty}^{\infty}\delta(t-lT_s-\mu T_s)e^{-j2\pi t\varepsilon}dt \tag{13}$$

where $\Im\{\cdot\}$ denotes the Fourier transform. Furthermore, by expressing the convolution, using a change of variables and the identity

$\Im\left[\sum_{l-\infty}^{\infty}\delta(t-lT_s)\right] = \dfrac{1}{T}\sum_{l=-\infty}^{\infty}\delta(\varepsilon-lT_s^{-1})$, one can show that (13) becomes

$$G_{OFDM}(\varepsilon,\tau)$$

$$= \int_{-\infty}^{\infty}\left(e^{-j2\pi\Delta f_c\tau}\sum_{k=0}^{K-1}C_s(t)e^{-j2\pi k\Delta f_k\tau}P[g(t)]P[g^*(t+\tau)]\right)$$

$$\otimes\sum_{l-\infty}^{\infty}\delta(t-lT_s-\mu T)e^{-j2\pi t\varepsilon}dt$$

$$= \frac{1}{T_s}e^{-j2\pi\Delta f_c\tau}e^{-j2\pi\varepsilon\mu T_s}\sum_{k=0}^{K-1}e^{-j2\pi k\Delta f_k\tau}\int_{-\infty}^{+\infty}C_s(t)P[g(t)]$$

$$\times P[g^*(t+\tau)]e^{-j2\pi t\varepsilon}dt\sum_{l=-\infty}^{+\infty}\delta(\varepsilon-lT_s^{-1}) \tag{14}$$

$$= \begin{cases}\dfrac{1}{T_s}e^{-j2\pi\Delta f_c\tau}e^{-j2\pi\varepsilon\mu T_s}\sum_{k=0}^{K-1}e^{-j2\pi k\Delta f_k\tau}\int_{-\infty}^{+\infty}C_s(t) \\ \times P[g(t)]P[g^*(t+\tau)]e^{-j2\pi t\varepsilon}dt & \varepsilon = lT_s^{-1} \\ \\ 0 & else\end{cases}$$

where $\Xi_k(\tau) = \sum_{k=0}^{K-1}e^{-j2\pi k\Delta f_k\tau} = e^{j\pi(1-K)\Delta f_k\tau}\dfrac{\sin(\pi K\Delta f_k\tau)}{\sin(\pi\Delta f_k\tau)}$. Note that (14) give the

analytical expressions for the generalized second-order cyclic statistics at $\varepsilon = lT_s^{-1}$ and certain delay. According to (14), when $\tau = 1/\Delta f_K = T_u$, $\Xi_k(\tau)$

yields significant peaks. Meanwhile, the magnitude peaks of $G_{OFDM}(\varepsilon,\tau)$ are visible at $\tau = T_u$ and $\varepsilon = lT_s^{-1}$, with l as an integer.

As one can notice, when processing the received signal $r(t)$ with nonlinear transformation, the modulated information of received signal $r(t)$ is maintained in the $G_{OFDM}(t,\tau)$. For the OFDM signal, significant peaks occur in the vicinity of $\tau = T_u$ and $\varepsilon = lT_s^{-1}$. $\Im\{G_w(t,\tau)\}$ stands for noise interference, and its impact has been suppressed due to the nonlinear transformation.

Similarly, for the SCLD signal, we obtain

$$
\begin{aligned}
G_{SCLD}(\varepsilon,\tau) = & T_c^{-1} e^{-j2\pi\Delta f_c\tau} e^{-j2\pi\varepsilon\mu T_c} \int_{-\infty}^{\infty} b(t)P\big[g(t)\big] \\
& \times P\big[g^*(t+\tau)\big]e^{-j2\pi t\varepsilon}dt \sum_{l=-\infty}^{+\infty}\delta(\varepsilon-lT_c^{-1})
\end{aligned}
\tag{15}
$$

where $b(t)$ is information data transmitted and the data is assumed to be i.i.d.. According to (15), the magnitude peaks of $G_{SCLD}(\varepsilon,\tau)$ are visible at $\tau = 0$ and $\varepsilon = lT_c^{-1}$.

3.2. The Generalized Cyclostationarity-Based Recognition Method of OFDM and SCLD Signals

Based on the above results on signal the generalized cyclic statistics, here we develop a novel algorithm for the recognition of OFDM and SCLD signals in alpha-stable noise.

Under the assumption of no aliasing, for the discrete-time signal $r(n) = r(t)\big|_{n=tf_s^{-1}}$, obtained by sampling the continuous-time signals $r(t)$ at the sampling rate f_s. According to the discussed in Section 3.1, we obtain

$$
\begin{aligned}
G(n,\tilde{\tau}) &= E\Big[f\big[r(n)\big]\cdot f^*\big[r(n+\tilde{\tau})\big]\Big] \\
&\approx E\left[\frac{s(n)s^*(n+\tilde{\tau})}{|s(n)||s(n+\tilde{\tau})|}\right] + E\left[\frac{w(n)w^*(n+\tilde{\tau})}{|s(n)||s(n+\tilde{\tau})|}\right] \\
&= G_s(n,\tilde{\tau}) + G_w(n,\tilde{\tau})
\end{aligned}
\tag{16}
$$

Then, for the OFDM signal, $G_s(n,\tilde{\tau})$ can be written as

$$
\begin{aligned}
G_{OFDM}(n,\tilde{\tau}) = & \left(e^{-j2\pi\Delta f_c\tilde{\tau}f_s^{-1}}\sum_{k=0}^{K-1}C_s(n)e^{-j2\pi k\Delta f_k\tilde{\tau}f_s^{-1}}\right. \\
& \left.\times P\big[g(n)\big]\times P\big[g^*(n+\tilde{\tau})\big]\right)\otimes \sum_{l=-\infty}^{\infty}\delta(n-lN_s-\mu N_s)
\end{aligned}
\tag{17}
$$

where $C_s(n) = E\left[\dfrac{a_k(n)a_k(n+\tilde{\tau})}{\overline{s}(n)\overline{s}(n+\tilde{\tau})}\right] \geq 0$,

$\overline{s}(n) = \left|\sum\limits_{k=0}^{K-1}a_k(n)e^{j2\pi k\Delta f_k n}\right|$, N_s denotes OFDM symbol length, and $N_s = N_u + N_{cp}$, $N_u = f_s/\Delta f_K$ is the useful symbol length and N_{cp} is the cyclic prefix length. From (17) one can see that $G_{OFDM}(n,\tilde{\tau})$ is a periodic function, with fundamental periodic N_s. Thus $G_{OFDM}(n,\tilde{\tau})$ can be expressed as a Fourier series, and the Fourier transform of (17) yields

$$G_{OFDM}(\upsilon,\tilde{\tau}) = \Im\{G_{OFDM}(n,\tilde{\tau})\}$$

$$= \sum_n \left(e^{-j2\pi\Delta f_c\tilde{\tau}f_s^{-1}} \sum_{k=0}^{K-1} C_s(n) e^{-j2\pi k\Delta f_k\tilde{\tau}f_s^{-1}} P[g(n)] \right.$$

$$\left. \times P[g^*(n+\tilde{\tau})] \right) \otimes \sum_{l=-\infty}^{\infty} \delta(n-lN_s-n_0) e^{-j2\pi\upsilon n} \tag{18}$$

$$= \frac{1}{N_s} e^{-j2\pi\upsilon\mu N_s} e^{-j2\pi\Delta f_c\tilde{\tau}f_s^{-1}} \sum_n \sum_{k=0}^{K-1} e^{-j2\pi k\Delta f_k\tilde{\tau}f_s^{-1}} C_s(n)$$

$$\times P[g(n)] P[g^*(n+\tilde{\tau})] e^{-j2\pi\upsilon n} \sum_{l=-\infty}^{+\infty} \delta(\upsilon-lN_s^{-1})$$

where $\Xi_k(\tilde{\tau}) = \sum_{k=0}^{K-1} e^{-j2\pi k\Delta f_k\tilde{\tau}f_s^{-1}} = e^{j\pi(1-K)\Delta f_k\tilde{\tau}f_s^{-1}} \dfrac{\sin(\pi K\Delta f_k\tilde{\tau}f_s^{-1})}{\sin(\pi\Delta f_k\tilde{\tau}f_s^{-1})}$, the significant

peaks of $\Xi_k(\tilde{\tau})$ can be obtained at $\tilde{\tau} = f_s / \Delta f_K = N_u$. Furthermore, from (18) it can be noticed that magnitude peaks are visible at $\tilde{\tau} = N_u$ and $\upsilon = l / N_s^{-1}$, with l as an integer.

Similarly, for the SCLD signal, we obtain

$$G_{SCLD}(\upsilon,\tilde{\tau}) = \Im\{G_{SCLD}(n,\tilde{\tau})\}$$

$$= N_c^{-1} e^{-j2\pi\Delta f_c\tilde{\tau}f_s^{-1}} e^{-j2\pi\upsilon\mu N_c} \sum_n \left(b(n)P[g(n)] \right. \tag{19}$$

$$\left. \times P[g^*(n+\tilde{\tau})] \right) e^{-j2\pi\upsilon n} \sum_{l=-\infty}^{+\infty} \delta(\upsilon-lN_c^{-1})$$

where $C(n) = E\left[\dfrac{b(n)b(n+\tilde{\tau})}{|b(n)||b(n+\tilde{\tau})|} \right] \geq 0$, $b(n)$ is information of data transmitted

and the data is assumed to be independent and identically distributed. N_c denotes symbol length of SCLD. According to (19), magnitude peaks of are visible at $\tilde{\tau} = 0$ and $\upsilon = lN_c^{-1}$, with l as an integer.

When comparing (18) and (19), one can easily notice the additional factor $\Xi_k(\tilde{\tau})$ which appears in the expression of the generalized cyclic statistics of the OFDM signal. One can easily show that significant peaks of the generalized cyclic statistics of OFDM signal yields at $\tilde{\tau} = 0$ and $\upsilon = lN_c^{-1}$. The existence of such a peak in the magnitude of the generalized cyclic statistics of the OFDM signal (at $\tilde{\tau} = N_u$ and $\upsilon = 0$) is employed as discriminating feature to identify OFDM against SCLD signals.

The estimate of the generalized cyclic statistics $\hat{G}(\upsilon,\tilde{\tau})$ exist the estimation error factor which vanishes asymptotically is $N \to \infty$. Due to the existence of estimation error factor, the estimator seldom exactly zero in practice, even if υ is not at generalized cycle frequencies. In order to decrease the impact of estimation error factor, referencing [10], the modulation classification features are given as,

$$\Psi = W\hat{C}_r^{\upsilon} \left(\hat{\Sigma}_r \right)^{-1} \left(\hat{C}_r^{\upsilon} \right)^{\dagger} \tag{20}$$

where $\hat{C}_r^{\upsilon} = \left[\mathrm{Re}\{\hat{G}(\upsilon,\tilde{\tau})\} \quad \mathrm{Im}\{\hat{G}(\upsilon,\tilde{\tau})\} \right]$, υ is tested candidate frequency and $\tilde{\tau}$ represents tested candidate delay, W is the received signal length. Here $\dagger$ and $(\cdot)^{-1}$ denote transpose and matrix inverse, $\hat{\Sigma}_r$ is an estimate of

the covariance matrix

$$\hat{\Sigma}_r = \begin{bmatrix} \mathrm{Re}\left\{(Q_{20}+Q_{21})/2\right\} & \mathrm{Im}\left\{(Q_{20}-Q_{21})/2\right\} \\ \mathrm{Im}\left\{(Q_{20}+Q_{21})/2\right\} & \mathrm{Re}\left\{(Q_{21}-Q_{20})/2\right\} \end{bmatrix} \tag{21}$$

with covariance estimators are respectively given by,

$$Q_{2,1} = \left(W\ell_w\right)^{-1} \sum_{v=-(\ell_w-1)/2}^{(\ell_w-1)/2} \omega(v) F^*\left(2\pi\upsilon + 2\pi v W^{-1}\right) \\ \times F\left(2\pi\upsilon + 2\pi v W^{-1}\right) \tag{22}$$

and

$$Q_{2,0} = \left(W\ell_w\right)^{-1} \sum_{v=-(\ell_w-1)/2}^{(\ell_w-1)/2} \omega(v) F\left(2\pi\upsilon - 2\pi v W^{-1}\right) \\ \times F\left(2\pi\upsilon + 2\pi v W^{-1}\right) \tag{23}$$

where $F(\upsilon) = \sum_{w=0}^{W-1} r(w+\tilde{\tau})r^*(l)e^{-j2\pi\upsilon w}$, $\omega(v)$ is a spectral window of support ℓ_w (odd).

According to the above analysis, the steps of recognizing OFDM against SCLD modulations may be obtained as follows:

Step 1: The magnitude of the generalized second-order cyclic statistics $\hat{G}(\upsilon,\tilde{\tau})$ of the received signal is estimated. Firstly, the discrete-time signal $r(n)$ obtained by sampling the continuous-time signal $r(t)$ at the sampling rate f_s. Then, the nonlinear transformation function in (8) is used to map received signal $r(n)$. Finally, the normalization magnitude of the second-order cyclic statistics $\hat{G}(\upsilon,\tilde{\tau})$ of the transformed signal $f\left[r(t)\right]$ is estimated.

Step 2: The modulation classification features Ψ is extracted from $\hat{G}(\upsilon,\tilde{\tau})$. Search the maximum $\hat{G}(0,\tilde{\tau})$ value at $\upsilon = 0$ section, and the delays $\tilde{\tau}$ in the interval $[\rho K_{\min}, \rho K_{\max}]$ (with and as the minimum and maximum number of subcarriers that we consider). Then, the modulation classification features Ψ is extracted with (20).

Step 3: The modulation type is decided. Classify the test signal by employing the SVM classifier defined in the training procedure.

4. Simulation Results and Analysis

A. Simulation setup

For the SCLD signals, we consider a pool of QPSK and 16-QAM. With the OFDM signals, the subcarriers are modulated using QPSK or 16-QAM. Unless otherwise mentioned, for the OFDM signal, the number of subcarriers is set to 64, the useful time period of the OFDM symbol is set to 0.0128 s and the cyclic prefix period is set to 0.0032s. In addition, frequency offset is set to 1 kHz and 2 kHz for SCLD and OFDM signals, and μ to 0.75, as θ a random variable uniformly distributed over $[-\pi,\pi]$. The SVM classifier is implemented by utilizing the LIBSVM toolbox, where the Gaussian RBF is selected as the kernel function. Let H_i be the training sequence composed of Ψ at the different MSNR, where $i \in \{1,\cdots,V\}$, with V as the number of the training sequences.

The number of training and test sequences is respectively set to 100 for each class at each MSNR.
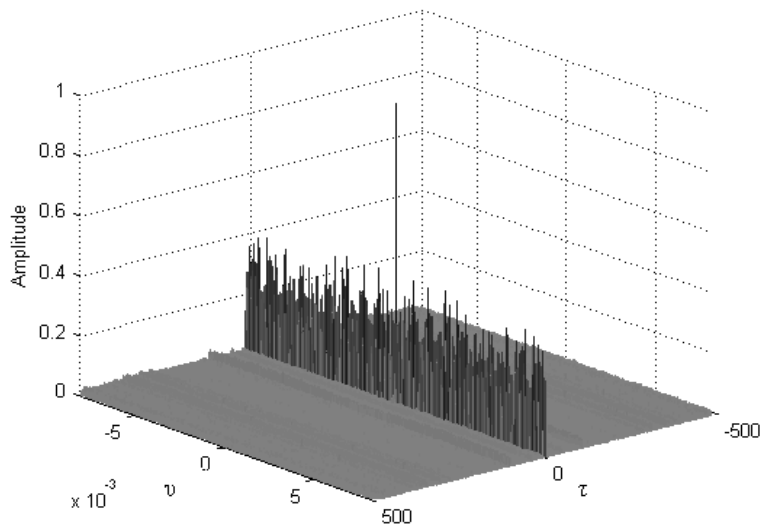
B. Generalized second-order cyclic statistics magnitude estimates for the OFDM and SCLD signals

The estimated magnitude of the generalized cyclic statistics of OFDM and SCLD is plotted. For SαS noise, MSNR = 10 dB and $\alpha = 1.5$.

When comparing results presented in **Figure 1** and **Figure 2**, one can notice that the second-order cyclic spectrum of OFDM signal is destroyed by alpha-stable noise, but the generalized second-order cyclic statistics of OFDM signal yields significant peaks at $\tilde{\tau} = N_u$ and $\upsilon = l / N_s^{-1}$. **Figure 3** shows that the generalized second-order cyclic statistics of SCLD signal can keep the characteristics of second-order cyclic statistics. However, **Figure 4** shows that the second-order cyclic statistics of SCLD signal is destroyed by alpha-stable noise. From **Figure 1** and **Figure 3** one can notice that the existence of such a peak in
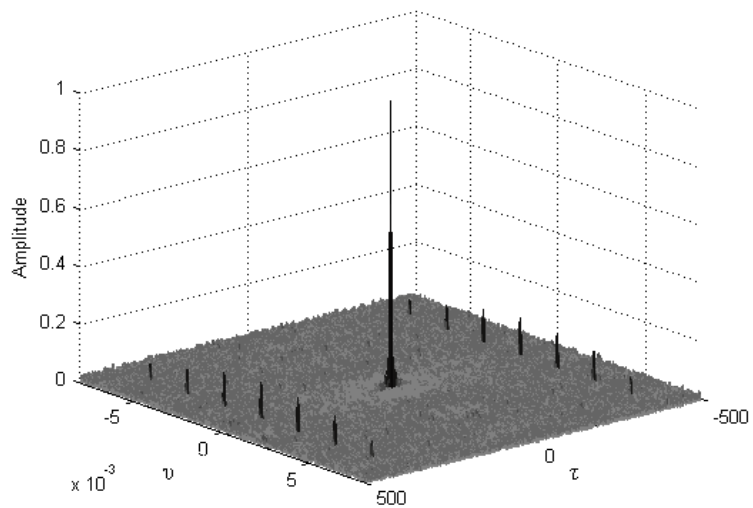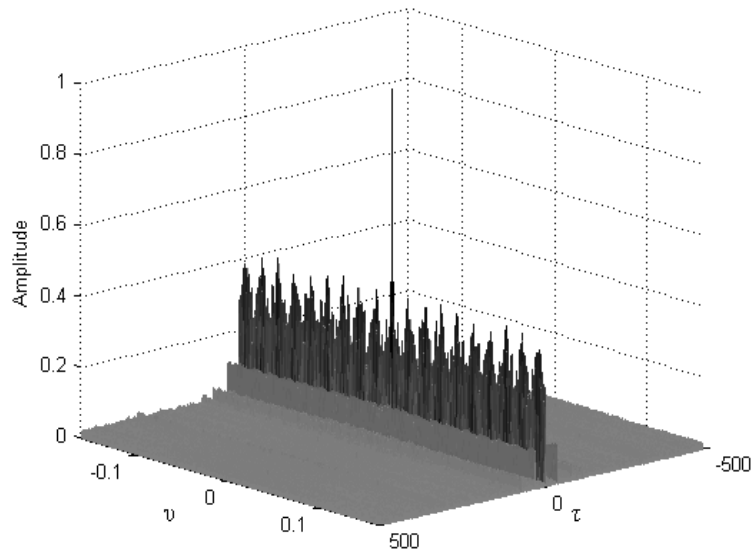

Figure 1. Generalized second-order cyclic statistics of OFDM signal.

Figure 2. Second-order cyclic statistics of OFDM signal.
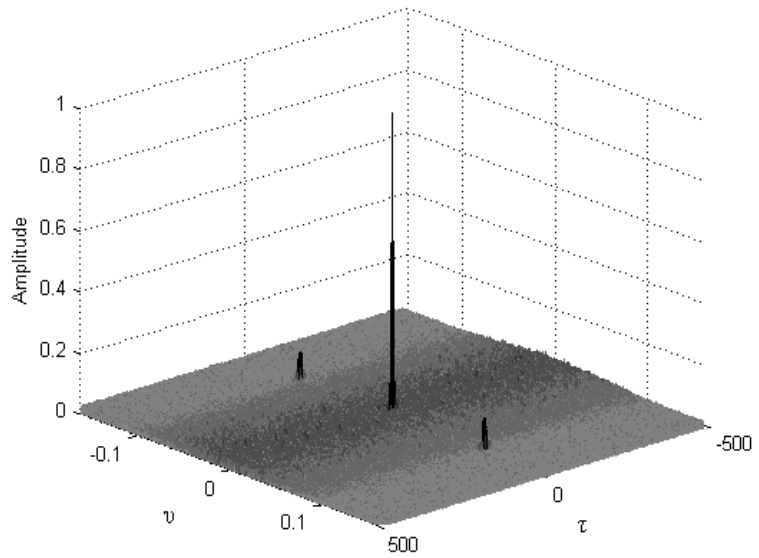
**Figure 3.** Generalized second-order cyclic statistics of SCLD signal.

Figure 4. Second-order cyclic statistics of SCLD signal.

the magnitude of the generalized cyclic statistics of the OFDM signal (at $\tilde{\tau} = N_u$ and $\upsilon = l / N_s^{-1}$) is employed as discriminating feature to recognize OFDM against SCLD signals.

### C. Performance of proposed recognition algorithm

Without loss of generality, set $\alpha = 1.5$. 200 tests for each MSNR value, and observation interval is set to 0.32 s. The simulation results are shown in **Figure 5**.

In **Figure 5**, the probability of correctly recognizing an OFDM signal is plotted versus MSNR. According to **Figure 5**, the algorithm based on traditional second-order cyclic statistics severely degraded within the range of the entire MSNR, but the proposed algorithm has a significant performance advantage. Note that the probability of correct detection and OFDM signal of the proposed
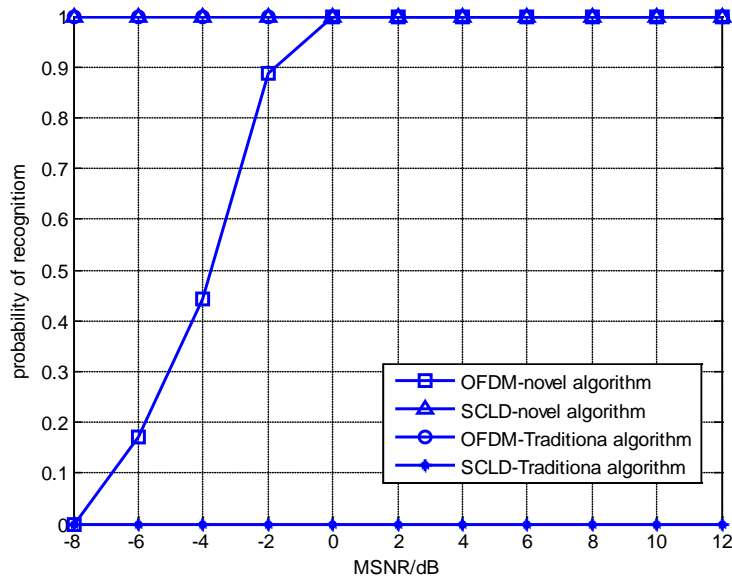
Figure 5. The probability of correct recognition in standard SαS noise.
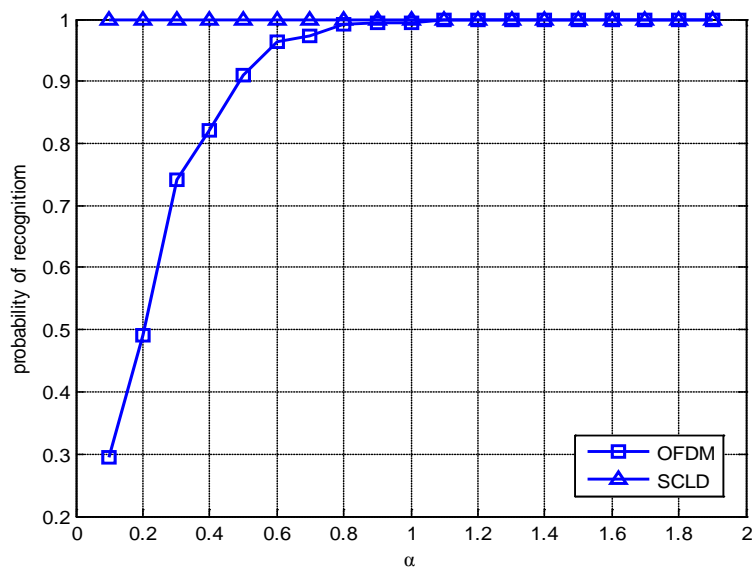
Figure 6. The probability of correct recognition with different values of α.

method is almost 100% at 0 dB. This simulation results for the algorithm performance confirm its effectiveness in alpha- stable distribution noise.

D. Effect of the α value on algorithm performance

In this experiment, set MSNR = 0 dB, α changes with the step 0.1 in the interval [0.1, 1.9]. The observation interval is set to 0.32 s, and 200 tests for each α value. The simulation results are shown in **Figure 6**.

Figure 6 shows performance results obtained for different values of α with the proposed algorithm. From **Figure 6** as can be seen simultaneously, the smaller the α value, the greater error of correct recognition. The reason is that the smaller α value and the more obvious peak characteristics of alpha-stable distribution. The probability of correct recognition of OFDM is 100%, when

$\alpha \geq 1$. This simulation result that the proposed method is suitable for different values of α in the interval [1, 2].

5. Conclusion

This paper proposes a novel modulation identification algorithm for OFDM and SCLD in alpha-stable distributed noise. The generalized second-order cyclic statistics can be exploited for the recognition of OFDM against SCLD signals. The proposed recognition algorithm eliminates the need for preprocessing tasks, such as symbol timing estimation, carrier and waveform recovery, and signal and noise power estimation. Simulation results show that the algorithm have good estimation performance and high robustness.

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