Amplitude Blind Estimation of Co-channel Time-Frequency Overlapped Signals

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Abstract. With the rapid development of wireless communication technology, modulation signals are more and more intensive in the same frequency. Based on the background of non-cooperative communication system, the research on blind estimation of time domain parameters of time-frequency overlapped signals is conducted. An amplitude estimation method of time frequency overlapped signal over single channel based on forth order cyclic cumulants is proposed. This method employs the fourth-order cyclic cumulants amplitude spectrum of the overlapped signal to estimate the amplitude at the cycle frequency of the respective signal symbol rate, thereby obtaining the amplitude estimation value of each signal component. Simulation results show that the proposed blind amplitude estimation method can achieve better estimation performance in low SNR conditions. Compared with the existing estimation method, the proposed method has better estimation performance.

Keywords: Amplitude estimation · Co-channel signal · Cyclic cumulants · Cyclic spectrum · Time-frequency overlapped signal

1 Introduction

Cooperative communication mode is the most commonly used communication mode in modern communication systems. That is, the receiver knows some relevant information in advance, such as the senders modulation type, communication system, carrier frequency, coding method, and other parameters such as amplitude, phase, phase, etc. However, in some practical applications, there is also a non-cooperative communication mode. Non-cooperative communication is an unauthorized access communication mode, which needs to be connected to

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the cooperative communication system and does not affect the normal communication of the cooperative communication parties [1,2]. In the non-cooperative communication mode, in order to successfully implement blind demodulation of the received signal, it is necessary to make a comprehensive and accurate estimation of the modulation parameters of the received signal. Therefore, parameter estimation of communication signals is an indispensable key technology in non-cooperative communication.

Signal parameter estimation refers to constructing sample function statistics, then substituting the sample values into the statistics, and using the observed values of the statistics as the estimated values of the corresponding parameters [3]. It is one of the important branches of mathematical statistics and a basic form of statistical inference. The parameter estimation of the time-frequency overlap signal refers to the extraction of parameter information about the signal from the intercepted received signal. The parameter estimation of the modulated signal includes the modulation parameters such as the carrier frequency, symbol rate, amplitude, initial phase and time delay of the received signal. estimate. At present, the research on parameter estimation of single signal is relatively mature, but the research on parameter estimation of time-frequency overlapping signal has some problems that need to be solved urgently.

In the radio communication process, due to the influence of factors such as channel fading and noise interference, the amplitude of the communication signal will change, which will have a greater impact on the estimation of the signal amplitude. For time-frequency overlapping signals, the amplitudes of the signal components cannot be separated when they are superimposed, which further increases the difficulty of amplitude estimation. Traditional signal amplitude estimation is mostly for a single signal, and there are mainly maximum likelihood estimation methods [4], which determine the signal amplitude based on the maximum likelihood estimation value of the sampled samples, but the amount of calculation is relatively large. Fourier spectrum analysis method [5,6], the disadvantage of this method is that there is spectrum leakage, which reduces the accuracy of signal amplitude estimation.

In view of the problem of poor amplitude estimation performance of existing methods when the signal-to-noise ratio is low, a amplitude estimation method of co-channel time-frequency overlapped signal based on the fourth-order cyclic cumulants is proposed. This method employs the fourth-order cyclic cumulants amplitude spectrum of the overlapped signal to estimate the amplitude at the cycle frequency of the respective signal symbol rate, thereby obtaining the amplitude estimation value of each signal component. Simulation results show that the proposed method effectively realizes the co-channel time-frequency overlapped signal amplitude parameter estimation. Moreover, the proposed method has strong anti-noise performance.

2 System Model

The model of time-frequency overlapped signal can be given as [7]

$$x(t) = \sum_{i=1}^{N} s_i(t) + n(t), \tag{1}$$

where $s_i(t) = \sum_{m=1}^{M_i} A_i a_i(m) q(t - mT_{bi} - \tau_i) \exp[j2\pi f_{ci} t + \theta_i]$. These elements A_i, $a_i(m)$, M_i and f_{ci} represent signal amplitude, symbol sequence , symbol number and carrier frequency of every signal component respectively. Also, T_i is a symbol cycle, whose reciprocal is symbol rate f_{ci}; θ_i is initial phase; $q_i(t)$ is pulse shape function. Note that if $q_i(t)$ is rectangular shape, it can be expressed as $q_i(t) = \begin{cases} 1, & |t| \le \frac{T_i}{2} \\ 0, & others \end{cases}$. If cosine raised, it can be expressed as $q_i(t) = \frac{\sin \pi t/T_i}{\pi t/T_i} \cdot \frac{\cos \alpha \pi t/T_i}{1-4\alpha^2 t^2/T_i{}^2}$, where $\alpha(\alpha = 0.35$ usually) is roll-off factor, τ_i is signal delay, n(t) is the additive Gaussian noise. Signals in this model are independent mutually, and the same to each signal and noise.

Assume that the number of overlapped signal i = 2. We do not consider the noise n(t) for simplification. Thus, the equation can be simplified as

$$\begin{aligned} x(t) &= A(t) e^{j\phi(t)} \\ &= A_1 e^{j(2\pi f_1 t + \varphi_1(t) + \theta_1)} + A_2 e^{j(2\pi f_2 t + \varphi_2(t) + \theta_2)} \\ &= A_1 e^{j\phi_1(t)} + A_2 e^{j\phi_2(t)}, \end{aligned} \tag{2}$$

where $\phi\,(t)$ is the phase function of the received overlapped signal, so that $\phi_1\,(t)$, $\phi_2\,(t)$ represent the 2 components phase function of overlapped signal in receiver respectively. $A(t)$ represents the amplitude function, and A_1, A_2 represent the 2 components amplitude function of overlapped signal. We can note that the vector sum of A_1, A_2 constitutes time-frequency overlapped signals amplitude $A(t)$.

3 Amplitude Estimation Based on Fourth-Order Cyclic Cumulants for Time-Frequency Overlapped Signal

Cyclostationarity is one of the prominent characteristics of digital communication signal. Hence, cyclic cumulant has been an effective tool to analyze digital communication signal. Given the property of cyclic cumulants, the cyclic cumulants of stationary and non-stationary Gaussian (color) noise is zero if its order is greater than 2, so that received signals cyclic cumulants have a good ability to resist noise. This paper proposes an amplitude estimation method about time-frequency overlapped signal by using 4-order cyclic cumulants.

The 4-order cyclic cumulants $C_{42}^{\alpha}\left(\tau_1, \tau_2, \tau_3\right)$ is defined as

$$\begin{aligned} C_{42}^{\alpha}\left(\tau_1, \tau_2, \tau_3\right) = M_{4s}^{\alpha}\left(\tau_1, \tau_2, \tau_3\right) - M_{2s}^{\alpha}\left(\tau_1\right) \cdot M_{2s}^{\alpha}\left(\tau_3 - \tau_2\right) \\ - M_{2s}^{\alpha}\left(\tau_2\right) \cdot M_{2s}^{\alpha}\left(\tau_1 - \tau_3\right) - M_{2s}^{\alpha}\left(\tau_3\right) \cdot M_{2s}^{\alpha}\left(\tau_2 - \tau_1\right). \end{aligned} \tag{3}$$

If $\tau_1 = \tau_2 = \tau_3 = 0$, (3) can be given as

$$C_{42}^{\alpha} \underline{\underline{\Delta}} C_{42}^{\alpha}(0,0,0) = M_{40}^{\alpha}(0,0,0) - 2M_{21}^{\alpha}(0) \cdot M_{21}^{\alpha}(0) - M_{20}^{\alpha}(0) \cdot M_{20}^{\alpha}(0), \quad (4)$$

and rewrite (3) as

$$C_{42}^{\alpha} = \begin{cases} \frac{A^4 C_{\alpha,42}}{T_s} \int_{-\infty}^{+\infty} \prod_{j=1}^{4} (q(t)) e^{-j2\pi\alpha t} dt, \alpha = \pm\frac{d}{T_s}, d \in Z, \\ \qquad 0, \qquad others, \end{cases} \quad (5)$$

where $C_{\alpha,42}$ is the 4-order cyclic cumulants value of $s(t)$. if $q(t)$ is raise cosine pulse, $C_{42}^{\alpha}(\tau_1, \tau_2, \tau_3)$ is non-zero in $\alpha = \pm d/T_s, d \in Z$. Besides, its maximum value appears at $\alpha = 0$ and the secondary is at $\alpha = \pm 1/T_s$.

We should notice that cyclic cumulants has another key property: signal selectivity. Considering the following multi-channel model, whose signals and noise are independent mutually. Co-channel signal can be expressed as follows

$$x(t) = s_1(t) + s_2(t) + \cdots + s_M(t) + n(t), \quad (6)$$

and its cyclic cumulants can be expressed as

$$C_{kx}^{\alpha}(\tau) = \sum_{i=1}^{M} C_{ks_i}^{\alpha}(\tau) + C_{kN}^{\alpha}(\tau). \quad (7)$$

For the cyclic cumulants of stationary and non-stationary Gaussian (color) noise is zero when the order of value is greater than 2, the 4-order cyclic cumulants of noise is 0. Hence, (7) can be written as

$$C_{kr}^{\alpha}(\tau) = \sum_{i=1}^{M} C_{kx_i}^{\alpha}(\tau). \quad (8)$$

Combining with the model in this section, the cycle frequency of time-frequency overlapped signal in the co-channel is

$$\alpha = \bigcup_{i=1}^{N} \alpha_i = \bigcup_{i=1}^{N} (k/T_{si}), k = 0, 1. \quad (9)$$

According to the property of cyclic cumulants, we can conclude that the cyclic cumulants has linear properties and the received signal in the single-channel is the linear combination of original signal. An achievement can be made that the cyclic cumulants to the received signal and the sum of every signals cyclic cumulants is the same. This property indicates that cyclic cumulants can reflect the cyclostationarity of every independent signal component and it is suitable for the estimation on time-frequency signal in the co-channel.

For MPSK signals, the expression can be written as

$$s(t) = \sum_{k} A a_k q(t - kT_s) e^{j(2\pi f_c t + \varphi_0)}, \quad (10)$$

where a_k is the symbol sequence of signals in interval $t \in (kT_s - T_s/2, kT_s + T_s/2)$, $a_k \in \left\{e^{j2\pi(m-1)/M}, m = 1, 2, \ldots, M\right\}$, and $q(t - nT_s)$ is cosine shaping pulse whose roll-off factor is 0.35. f_c, T_s and φ_0 are carrier frequency, symbol period and initial phase, respectively.

Substitute the expression of MPSK signals into the definition of 4-order cyclic cumulants and MPSK signals 4-order cyclic cumulants can be given as

$$C_{42-MPSK}^{\alpha} = \frac{A^4 C_{\alpha,42}}{T_s} \int_{-\infty}^{+\infty} \prod_{j=1}^{4} (q(t)) e^{-j2\pi\alpha t} dt, \tag{11}$$

where $\mathrm{C}_{\alpha,42}$ is 4-order cumulants value of $s(t)$. For QPSK signals, because $a_k = e^{j(m-1)2\pi/4}, m = 1, 2, \cdots, 4$ and $a_k^2 = \pm j, a_k^4 \equiv 1$, QPSK signals 4-order cumulants is

$$\mathrm{C}_{\alpha,42-\mathrm{QPSK}} = M_{\alpha,42} - 2(M_{\alpha,21})^2 - |M_{\alpha,20}|^2 = -\frac{1}{N} \sum_{k=1}^{N} {a_k}^4 = -1. \tag{12}$$

Further more, the 4-order cyclic cumulants of the signal is

$$C_{42-QPSK}^{\alpha} = -\frac{A^4}{T_s} \int_{-\infty}^{+\infty} \prod_{j=1}^{4} (q(t)) e^{-j2\pi\alpha t} dt. \tag{13}$$

The $|C_{42}^{\alpha}|$ value of QPSK signals is shown in Fig. 1. From Fig. 1, we can see that the maximum value of $|C_{42}^{\alpha}|$ appears at $\alpha = 0$, and the secondary at $\alpha = \pm 1/T_s$. So that we can estimate signals component amplitude based on the value of great discrete spectrum line.

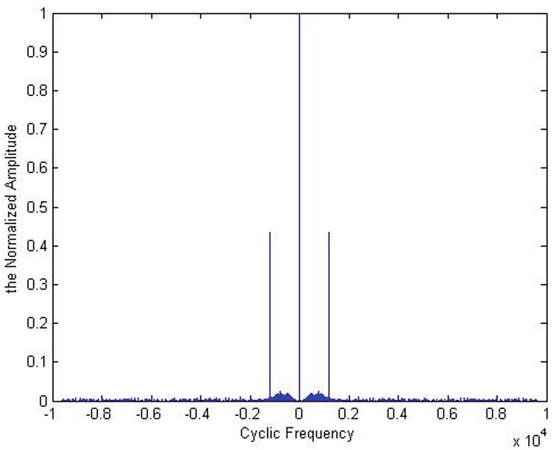

Fig. 1. $|C_{42}^{\alpha}|$ of co-channel two QPSK overlapped signals.

For 8PSK signals, because of $a_k = e^{j(m-1)2\pi/8}, m = 1, 2, \cdots, 8$, whose 4-order cumulants is given as

$$\mathrm{C}_{\alpha,42-8\mathrm{PSK}} = M_{\alpha,42} - 2(M_{\alpha,21})^2 - |M_{\alpha,20}|^2 = -\frac{1}{N}\sum_{k=1}^{N} {a_k}^4 = -1. \tag{14}$$

Hence, the 4-order cyclic cumulants of 8PSK can be expressed as follows:

$$C^{\alpha}_{42-8PSK} = -\frac{A^4}{T_s}\int_{-\infty}^{+\infty}\prod_{j=1}^{4}(q(t))e^{-j2\pi\alpha t}dt. \tag{15}$$

For 16QPSK signals, because of $a_k = e^{j(m-1)2\pi/16}, m = 1, 2, \cdots, 16$, the 4-order cumulants is given as

$$\mathrm{C}_{\alpha,42-16\mathrm{PSK}} = M_{\alpha,42} - 2(M_{\alpha,21})^2 - |M_{\alpha,20}|^2 = -\frac{1}{N}\sum_{k=1}^{N} {a_k}^4 = -1. \tag{16}$$

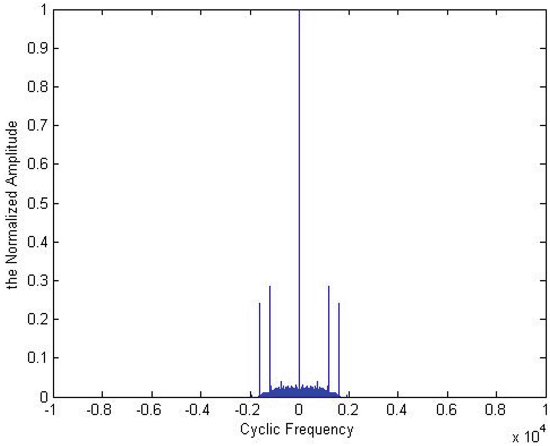

Fig. 2. $|C^{\alpha}_{42}|$ of co-channel QPSK and 16PSK overlapped signals.

From the above analysis, PSK signals, QPSK, 8PSK and 16PSK have the same expression for 4-order cyclic cumulants. More importantly, the value of their cyclic cumulants are non-zero at the cycle frequency $\alpha = \pm k/T_s, k \in Z$, the maximum value at $\alpha = 0$, and the secondary at $\alpha = \pm 1/T_s$. The following figure shows two mixed signals $|C^{\alpha}_{42}|$ value. In Fig. 2, the maximum value of $|C^{\alpha}_{42}|$ appears at $\alpha = 0$, but signals are overlapped and cant be distinguished. Every signal components discrete spectrum line exists in the area where the cycle frequency equals the symbol rate. If $\alpha = \pm 1/T_s$ and roll-off coefficient of raised cosine takes a fixed value, the integral term of 4-order cyclic cumulants

$\int_{-\infty}^{+\infty} \prod_{j=1}^{4} (q(t))e^{-j2\pi\alpha t}dt$ is given by constant number and be expressed by G_i. It is only in this case that the symbol rate of time-frequency overlapped signals component are not equal and do not exist any integer multiple relationship, can we estimate the symbol cycle T_{s_i} by detecting the position of discrete spectrum line. This paper uses raised discrete spectrum line to estimate discrete spectrum line. Specific process is as follows:

Assuming that $u(f)$ is the amplitude spectrum of 4-order cyclic cumulants, where f_0 means the frequency when $|u(f)|$ takes the maximum. Using the ratio of $|u(f_0)|$ and the mean of $|u(f)|$ to express the prominence of f_0. If the ratio is bigger than a certain threshold, there shall be a discrete spectrum line atf_0. Because of frequency resolution, there are many approximate discrete spectrum line of 4-order cyclic cumulants but only one. In order to prevent these discrete spectrum line which has a bad effect when searching the maximum during the next time, we need to set $|u(f)|$ zero in a section $[f_0 - \delta_0, f_0 + \delta_0]$, where $\delta_0 > 0$. If $\alpha_1 = 1/T_1$, $\alpha_2 = -1/T_1$, the first signal components symbol cycle $\hat{T}_1 = \frac{2}{|\alpha_1 - \alpha_2|}$. In the same way, we can estimate symbol cycle of other signals. Substituting these values into the above formula respectively, we can acquire the value of every signals amplitude estimation.

From the above, a amplitude blind estimation of time-frequency overlapped signals based on 4-order cyclic cumulants in co-channel is proposed, and the steps of the proposed method are as follows:

Step 1: Search the value of 4-order cyclic cumulants $\left|C_{r,42}^{\alpha}\right|$ of time-frequency overlapped signals $r(t)$ in single channel, then get the amplitude spectrum of 4-order cyclic cumulants overlapped signals $\alpha - \left|C_{r,42}^{\alpha}\right|$;

Step 2: When the symbol rate of time-frequency overlapped signals component is not equal and does not exist integer multiple relationship, we can estimate the symbol rate of signal component $1/T_{s_i}$, according to discrete spectrum line detection method;

Step 3: In the light of the symbol rate $1/T_{s_i}$, search the value of $C_{x,40}^{1/T_{s_i}}$ in $\alpha - \left|C_{r,42}^{\alpha}\right|$ when $\alpha_i = 1/T_{s_i}$;

Step 4: According to the value of step 2 and step 3, search the amplitude estimation value of every signal component $\hat{A}_i = \sqrt[4]{|C_{42}^{\alpha}| \cdot T_{s_i}/G_i}$.

4 Simulation Results and Discussion

Simulation experiment has been done by using MATLAB to validate the effectiveness of the estimation method in this paper. Time-frequency overlapped signals and additive white gaussian noise are adopted in this experiment. In order to assess the performance of the method in different ways, we take different kinds of signals (QPSK, 8PSK and 16PSK) into simulation experiment, and the coefficient of roll-off is 0.35. It also takes 1000 Monte Carlo tests. The evaluation criteria of amplitude estimation is MSE.

In order to measure the SNRs effects on the performance of amplitude estimation on time-frequency overlapped signals, we can put the arbitrary combination of two in QPSK, 8PSK and 16PSK signals, and the parameter setting is as follows: carrier frequency $f_{c1} = 2.7$ KHz and $f_{c2} = 3.3$ KHz; symbol rate $f_{b_1} = 1.2$ KBaud and $f_{b2} = 1.6$ KBaud; sample rate $f_s = 19.2$ KHz; data length 5000. The simulation result is shown in Fig. 3.

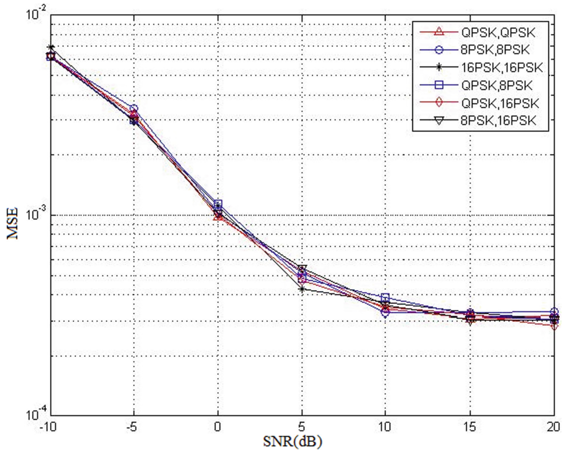

Fig. 3. Amplitude estimation performance of time-frequency overlapped signals with different SNRs.

As can be seen from the Fig. 3, in the case of double overlapping signals, when the SNR is bigger than 0, the method of amplitude estimation can achieve ideal estimation performance, and with the increase of SNR , the estimation performance increase.

In order to test the influence of sample data length to the amplitude estimation of time-frequency overlapped signals, we can put the arbitrary combination of two in QPSK, 8PSK and 16PSK signals, and the SNR is 10 dB. the parameter setting is as follows: carrier frequency $f_{c1} = 2.7$ KHz and $f_{c2} = 3.3$ KHz; symbol rata $f_{b_1} = 1.2$ KBaud and $f_{b2} = 1.6$ KBaud; sample rata $f_s = 19.2$ KHz. the simulation results are as Fig. 4.

From Fig. 4, with the increase of sample data length, the estimated performance increases for the decrease of the amplitude estimation MES from time-frequency overlapped double signals. The reason is that cyclostationarity which is reflected by cyclic cumulants is an asymptotic property, so that the estimation performance of amplitude estimation method can be improved by increasing the data length.

In order to measure the influence of spectrum overlap rate to the performance of amplitude estimation on time-frequency overlapped signals, we can put the arbitrary combination of two in QPSK, 8PSK and 16PSK signals, and the SNR is 10 dB. The parameter setting is as follows: sample rate $f_s = 19.2$ KHz, data length is 5000, carrier frequency combination are $f_{c1} = 1.9$ KHz and $f_{c2} = 3.3$

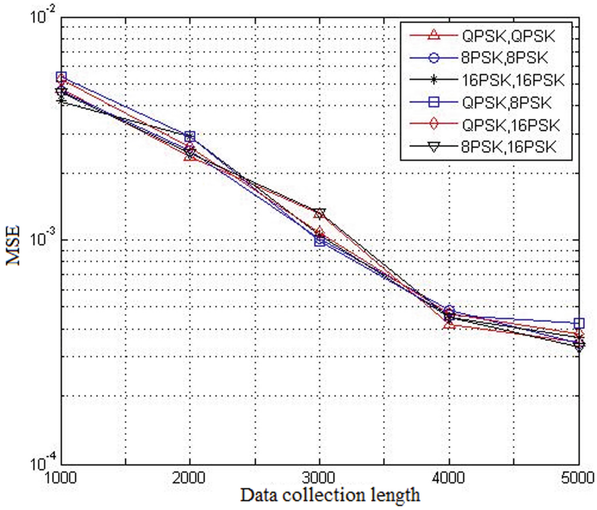

Fig. 4. Amplitude estimation performance of time-frequency overlapped signals with different data length.

KHz; f_{c1} = 2.2 KHz and f_{c2} = 3.3 KHz; f_{c1} = 2.5 KHz and f_{c2} = 3.3; KHz f_{c1} = 3.1 KHz and f_{c2} = 3.3 KHz respectively. Symbol rate f_{b1} = 1200 Baud and f_{b2} = 1600 Baud.The simulation results are shown in Fig. 5.

As can be seen from Fig. 5, spectrum overlap rate has a little influence on amplitude estimation. The reason is that when data length is fitful, if the symbol rate of signal component is different, using cyclic cumulants of signals to estimate amplitude is helpful in distinguishing different signals amplitude information, while its performance will not be affected by other signals.

In order to measure the influence of power ratio to the performance of amplitude estimation on time-frequency overlapped signals. We can put the arbitrary combination of two in QPSK, 8PSK and 16PSK signals, and the SNR is 10 dB. the power ratio of two signals is 1.2. The parameter setting of the two signals is as follows: carrier frequency f_{c1} = 2.7 KHz and f_{c2} = 3.3 KHz; symbol rate f_{b_1} = 1.2 KBaud and f_{b2} = 1.6 KBaud; sample rate f_s = 19.2 KHz ; data length 5000. The simulation results are as Fig. 6.

From Fig. 6, which compares with Fig. 3 whose power ratio is 1.0, the increase of signals component s power ratio can make the estimation performance decrease. When the power ratio of two signals is 1:2 and the SNR is 10 dB, the amplitude estimation method can achieve an ideal performance. As the 4-order cyclic cumulants estimation in face is done with the biquadrate magnitudes of signals, so that the change of signals power can bring a big change to the 4-order cyclic cumulants.

In order to compare the performance of the method in this paper with the existing method, the overlapped signals are two misxed QPSK. In the same simulation environment and the parameter setting, the method in this paper has to compare with the method in [12]. The result is shown in Fig. 7.

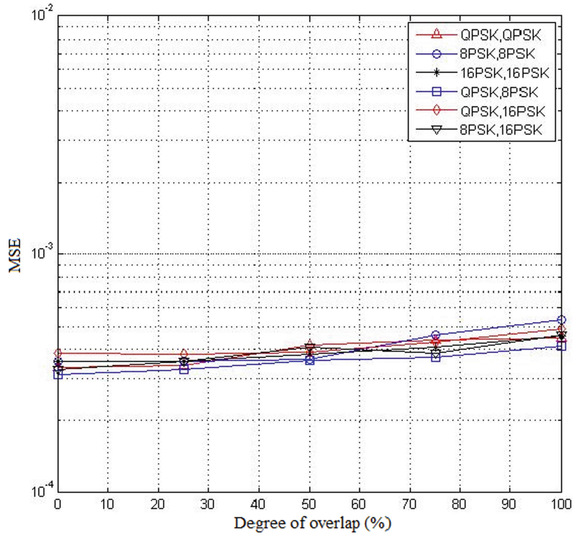

Fig. 5. Amplitude estimation performance of time-frequency overlapped signals with different spectrum overlap rates.

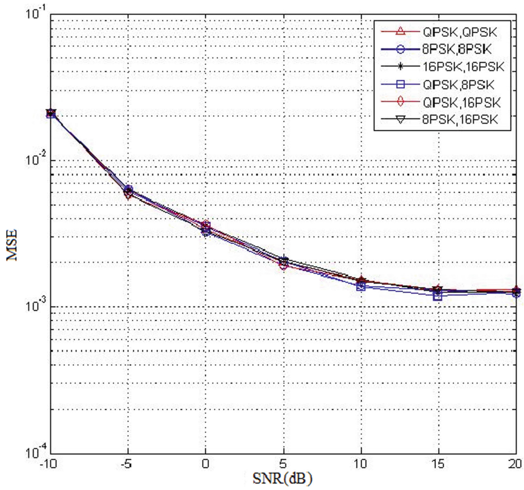

Fig. 6. Amplitude estimation performance of time-frequency overlapped signals when the power ratio is 1.2

As can be seen in Fig. 7, in the same simulation condition, the method in this paper has a better performance than the method which is based on max-min method. In the case of low SNR, the max-min arithmetic does not have an ideal estimation performance. But the method in this paper can be better, due to that cyclic cumulants can suppress noise. The method in [12] needs $4(M+N)-6$ times

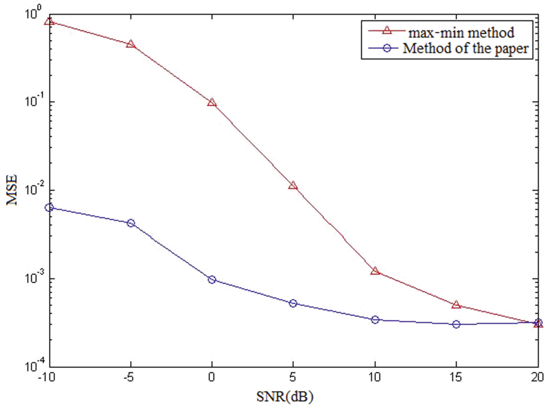

Fig. 7. Amplitude estimation performance comparison with different methods

addition of complex number and 4N multiplication of complex number, where M is window length; in this paper, the times of addition and multiplication of complex are $2N\log_2 N + N$ and $[N\log_2 N + 5N$, so that the algorithm complexity in this paper is bigger, but the performance is better than the method in [12], especially in the low SNR condition.

5 Conclusion

In order to to solve the poor performance in amplitude estimation when the SNR is low, this paper introduces an amplitude estimation method based on the 4-order cyclic cumulants for time-frequency overlapped signals in co-channel. Simulation results show that the proposed method has a good anti-noise performance. Moreover, the proposed method has better estimation performance compared with the existing methods.

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