TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol.12, No.3, March 2014, pp. 1911 ~ 1916
DOI: http://dx.doi.org/10.11591/telkomnika.v12i3.4156

Modulation Recognition Based on Feature Extraction by AutoRegressive Model

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Abstract

Through the research of the digital modulation signals, we find that the signal would produce a series of spectrum lines after a specific nonlinear transformation. Therefore, this characteristic has a certain potential in the signal modulation recognition. In this paper, first, we analyze the spectrum lines mechanism of modulation signals (4PAM, BPSK, QPSK, 8PSK, 2FSK, 4FSK), then, we use AR model to extract the spectrum lines characteristics of modulation signals to identify different signals. In the end of the paper, the above-mentioned six signals are simulated in the MATLAB environment. Simulation results show that the recognition of the modulation signals through this method has good stability in non-ideal communication environment.

Keywords: *modulation recognition, AR model, spectrum lines feature, nonlinear transformation*

1. Introduction

The modern communication environment are increasingly complex, the digital modulation signals (such as M-ary phase shift keying (MPSK)、M-ary frequency shift keying (MPSK)、pulse amplitude modulation (PAM) signals) are widely used in digital communication, therefore the limitations of the traditional modulation recognition methods are more and more prominent. This allows the importance of automatic identification technology of digital modulation signals growing.

In recent years, many researchers are committed in the study of modulation signals feature extraction methods, and they have achieved fruitful results [1-4]. Researches show that it have been difficult to solve the modulation recognition based on the transient characteristics under complex electromagnetic environment, therefore it makes the time-frequency analysis gradually been widely used in the modulation recognition field, the frequency domain characteristics are gradually applied to the modulation recognition research [5, 6]. However, time-frequency analysis still have some inherent imperfections, such as it is difficult to balance the time and frequency accuracy in the STFT, the WVD method can not eliminate the impact of cross-terms. So these algorithms have their inherent limitations in dealing with some specific modulation recognition problems, lower accuracy and higher complexity, timeliness is not good enough.

Through the study of modulation signals, we found that they will produce a series of spectral lines through some nonlinear transformations, in this paper we use a method of spectrum lines extraction based on AR model to identify the digital modulation signals. The spectral lines characteristics of digital modulation signals after a nonlinear transformation are intrinsically linked to the signal modulation modes and modulation parameters, in addition, they have good robustness and are extracted easily in non-ideal communication environment [9]. First, we analyze the spectrum lines mechanism of modulation signals through nonlinear transformation, and identify the digital modulation signals through these characteristics extraction; Then, we model the digital modulation signals after a nonlinear transformation into AR model, estimate the spectral lines characteristics using the HOYW equation; Finally, we design appropriate recognition algorithm for 4PAM, BPSK, QPSK, 8PSK, 2FSK, 4FSK signal identification based on the above characteristics. Simulation results show that the modulation recognition method based on spectral lines extraction in this paper has better stability than the conventional modulation recognition method.

Received August 14, 2013; Revised September 28, 2013; Accepted October 16, 2013

2. Signal Model of Common Digital Signals

In real life, most channels have the band-pass characteristic, so the baseband signals can not be transmitted directly. Therefore, we use the digital baseband signal to control the carrier, convert the digital baseband signal into digital bandpass signal, this modulation process is called digital modulation, and this modulation signal is called digital modulation signal. Common digital modulation signals as: MFSK、MPSK、PAM and so on. Here are the mathematical models of these three modulation signals [7].

The general plural form of digital modulation signals is:

$$S(t) = \sum_n a_n g(t - nT) e^{j[2\pi m/M + \varphi]} \tag{1}$$

Where $g(t)$ is the root mean square raised cosine roll-off function, assume:

$$U_n = \sum_n a_n g(t - nT)$$

The mathematical model of MPSK signals:

$$S(t) = U_n e^{j(2\pi f_c t + 2\pi m/M)} \tag{2}$$

The mathematical model of MFSK signals can be described as:

$$S_{FSK}(t) = \sqrt{2E_s/T} \sum_n g(t - nT) e^{j(2\pi m \Delta f t)} \tag{3}$$

Where $m = 1, 2, \cdots, M$; carrier spacing $\Delta f = 1/2T$; $g(t)$ is the rectangular pulse.

The baseband form of PAM signals can be described as:

$$S(t) = \sum_n A_n g(t - nT) \tag{4}$$

Where A_n signifies the symbol sequence, $g(t)$ represents the raised cosine pulse, α is the roll-off factor, non-zero bandwidth is $\left(-(1+\alpha)/2T, (1+\alpha)/2T\right)$.

3. Signal Spectral Lines Analysis

The study finds that the digital modulation signal after a specified nonlinear transformation often exhibits different spectral characteristics. The following, respectively from the theoretical analysis point and simulation point, analyze the spectral characteristics and generation mechanism of FSK、PSK、PAM signals which have been processed power transformation.

Assuming $x(t)$ is random signal, power transformation can be described as:

$$V_a(x(t)) = [x(t)]^a \text{。}$$

3.1. Frequency-Modulated signal

Take the 2FSK signal as an example to analyze the power spectral characteristics. The signal respectively through square and fourth power nonlinear transformation is [8]:

$$V_2(S(t)) = 2E_s/T \sum_n g(t - nT) e^{j(2\pi 2m \Delta f t)} \tag{5}$$

$$V_4\left(S(t)\right)=\left(2E_s/T\right)^2\sum_n g\left(t-nT\right)e^{j(2\pi 4m\Delta ft)} \tag{6}$$

It can seen that the square spectrum and the fourth-power spectrum of 2FSK signals have two independent lines at the points of $\pm 2\Delta f$ and $\pm 4\Delta f$ respectively.

3.2. Phase-Modulated Signal

The phase-modulated signal after a -th power nonlinear transformation is [9]:

$$V_a\left(S(t)\right)=\left[U_n e^{j(2\pi f_c t+2\pi m/M)}\right]^a=U_n{}^a e^{j(2\pi a f_c t+2\pi am/M)} \tag{7}$$

Its power spectrum is: $V_a\left(f\right)=F\left[V_a\left(S(t)\right)\right]=F\left[U_n{}^a e^{j(2\pi a f_c t+2\pi am/M)}\right]$

Available: There are clear spectral lines at the carrier frequency point of square spectrum、fourth-power spectrum and eighth-power spectrum of BPSK; The square spectrum of QPSK do not have clear spectral lines, but fourth-power and eighth-power spectrum have clear spectral lines at the point of carrier frequency; Clear spectral lines do not appear in square spectrum and fourth-power spectrum of 8PSK, there are clear spectral lines at carrier frequency point in eighth-power spectrum.

3.3. Pulse Amplitude Modulated Signal

The power spectrum of PAM signals after square and fourth-power transformation:

$$V_2\left(f\right)=\frac{E_s}{T}\sum_n G\left(f\right)*G\left(f\right)\delta\left(f-\frac{n}{T}\right) \tag{8}$$

$$V_4\left(f\right)=\frac{E_s{}^2}{T^2}\left\{\sum_n G\left(f\right)*G\left(f\right)\delta\left(f-\frac{n}{T}\right)\right\}*\left\{\sum_m G\left(f\right)*G\left(f\right)\delta\left(f-\frac{m}{T}\right)\right\} \tag{9}$$

E_s represents the mean energy of symbols. The characteristics of raised cosine pulse shows that the nonzero bandwidth of $G(f)*G(f)$ is $\left(-\frac{1+\alpha}{T},\frac{1+\alpha}{T}\right)$. Thus analysis shows that spectral lines appear at the points of $f\in\{0,\pm 1/T\}$ and $f\in\{0,\pm 1/T,\pm 2/T\}$ in the square and fourth-power spectrum of 4PAM signals.

4. Extraction of Signal Spectral Characteristics

Take 2PSK as an example, after the square transformation, we get:

$$V_2\left(S(t)\right)=\left[U_n e^{j(2\pi f_c t+\pi m)}\right]^2=U_n{}^2 e^{j(4\pi f_c t+2\pi m)}=U_n{}^2 e^{j4\pi f_c t} \tag{10}$$

Then,

$$\left(1-e^{j4\pi f_c}z^{-1}\right)V_2\left(S(t)\right)=0 \tag{11}$$

Make assumption that the noise and source signals are not relevant, then:

$$A(z)y(t)=A(z)e(t) \tag{12}$$

Where $A(z)=\left(1-e^{j4\pi f_c}z^{-1}\right)$, $y(t)=V_2\left(S(t)\right)+e(t)$.

Assume $\bar{A}(z)$ a $(N-1)$th-order polynomial, multiply it by formula (12), we can get a higher order ARMA formula:

$$y(t)+b_1 y(t-1)+\cdots+b_N y(t-N)=e(t)+b_1 e(t-1)+\cdots+b_N e(t-N) \tag{13}$$

Or $B(z)y(t)=B(z)e(t)$, where $B(z)=A(z)\cdot\bar{A}(z)$.
Then:

$$\left[y(t)\,y(t-1)\cdots y(t-N)\right]\left[1\cdots b\right]^T=e(t)+b_1 e(t-1)+\cdots+b_N e(t-N) \tag{14}$$

Left multiply formula (14) by $\left[y^*(t-N-1)\cdots y^*(t-N-M)\right]^{\mathrm{T}}$, and take its expectation:

$$\mathbf{\Gamma}^c\begin{bmatrix}1\\ \mathbf{b}\end{bmatrix}=0,\ \text{where}\ \mathbf{\Gamma}=\mathrm{E}\left\{\begin{bmatrix}y(t-N-1)\\ \vdots\\ y(t-N-M)\end{bmatrix}\left[y(t)\,y(t-1)\cdots y(t-N)\right]\right\}$$

Make the above equation written in the form of HOYW equations:

$$\begin{pmatrix}r(N) & \cdots & r(1)\\ \vdots & \ddots & \vdots\\ r(N+M-1) & \cdots & r(M)\end{pmatrix}\mathbf{b}=-\begin{pmatrix}r(N+1)\\ \vdots\\ r(N+M)\end{pmatrix} \tag{15}$$

Through the above theoretical analysis [10], use the HOYW equations to estimate the spectral line frequency of nonlinear transformed digital modulation signals.

$\hat{r}(k)$ is the covariance of the sample, then:

$$\begin{pmatrix}\hat{r}(N) & \cdots & \hat{r}(1)\\ \vdots & \ddots & \vdots\\ \hat{r}(N+M-1) & \cdots & \hat{r}(M)\end{pmatrix}\hat{\mathbf{b}}\approx-\begin{pmatrix}\hat{r}(N+1)\\ \vdots\\ \hat{r}(N+M)\end{pmatrix} \tag{16}$$

Assume $\hat{\boldsymbol{\Omega}}=\begin{pmatrix}\hat{r}(N) & \ldots & \hat{r}(1)\\ \vdots & \ddots & \vdots\\ \hat{r}(N+M-1) & \cdots & \hat{r}(M)\end{pmatrix}$, Since there exists the random error in $\{\hat{r}(k)\}$, $\hat{\boldsymbol{\Omega}}$ is approximate full rank, $\operatorname{rank}(\hat{\boldsymbol{\Omega}})=\min(M,N)$. So assume that :

$\hat{\boldsymbol{\Omega}}=\mathbf{U\Sigma V}^*\cong\left[\underbrace{\mathbf{U}_1}_{n}\ \underbrace{\mathbf{U}_2}_{M-n}\right]\begin{bmatrix}\mathbf{\Sigma}_1 & 0\\ 0 & \mathbf{\Sigma}_2\end{bmatrix}\begin{bmatrix}\underbrace{\mathbf{V}_1^*}_{n}\\ \underbrace{\mathbf{V}_2^*}_{N-n}\end{bmatrix}$ represents the singular value decomposition of $\hat{\boldsymbol{\Omega}}$, where $\mathbf{U}$ is $M\times M$ unitary matrix, $\mathbf{V}$ is $N\times N$ unitary matrix, $\mathbf{\Sigma}$ is $M\times N$ diagonal matrix.

$\hat{\boldsymbol{\Omega}}$ is a matrix whose rank approaches to n, this shows that $\hat{\boldsymbol{\Omega}}_n\cong\mathbf{U}_1\mathbf{\Sigma}_1\mathbf{V}_1^*$ is a very good approximation to $\hat{\boldsymbol{\Omega}}$.

Thus, we can get rank truncated HOYW equations:

$$\hat{\boldsymbol{\Omega}}_n\hat{\mathbf{b}}\approx-\left(\hat{r}(N+1)\cdots\hat{r}(N+M)\right)^T \tag{17}$$

So the LS solution of the formula above is: $\hat{\mathbf{b}} \approx -\mathbf{V}_1\mathbf{\Sigma}_1^{-1}\mathbf{U}_1^{*}\left(\hat{r}(N+1)\ldots\hat{r}(N+M)\right)^T$

Then the solution of HOYW equations is: $\hat{\mathbf{b}} \approx -\mathbf{V}_1\mathbf{\Sigma}_1^{-1}\mathbf{U}_1^{*}\left(\hat{r}(N+1)\ldots\hat{r}(N+M)\right)^T$, so there comes polynomial: $1+\sum_{k=1}^{N}\hat{b}_k z^{-k}$, In the formula, the nearest angular position is the $\hat{z}_n$.

In the MATLAB environment, based on the AR model estimation, the spectral characteristics of 2PSK and 4PAM signals after a square transformation, select the carrier frequency as 3Hz, symbol rate 1B, sampling frequency 3kHz, then the spectral characteristics is just as Figure 1, 2 and 3 showing.

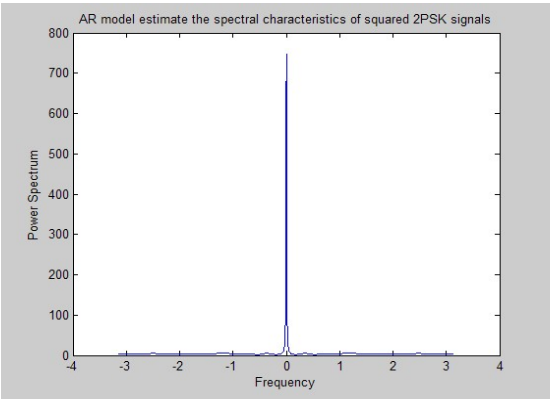

Figure 1. Use AR Model to Estimate the Spectral Characteristics of Squared 2PSK Signals

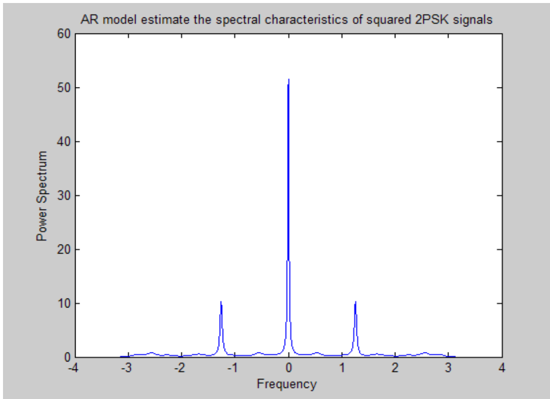

Figure 2. Use AR Model to Estimate the Spectral Characteristics of Squared 4PAM Signals

5. The Algorithm of Modulation Recognition

For the theoretical analysis of the previous section, intend to take the algorithm below to do modulation recognition for the digital modulation signals (4PAM, BPSK, QPSK, 8PSK, 2FSK, 4FSK):

1) Do square transformation for digital modulation signals, calculate the power spectrum of square transformed signals.
2) Use AR model to estimate its spectral line frequency of square-spectrum, according to the number of spectral line frequency of square-spectrum, there are four categories of signals: 4PAM (3 spectral line frequency), 2PSK(1 spectral line frequency), 4PSK and 8PSK (no clear spectral lines), 2FSK and 4FSK (2 spectral line frequency)。
3) 2FSK signals and 4FSK signals can be separated by the difference of spectral line frequency, two spectral line frequency of 2FSK is $\pm 2\Delta f$, while 4FSK signals is $\pm 4\Delta f$
4) Do square transformation for the nonlinear transformed signals, calculate its power spectrum.
5) 4PSK and 8PSK can be recognized by using AR model to estimate the spectral line frequency, 4PSK have a clear spectral line, while 8PSK have no clear spectral lines.

Therefore, we can identify the specific types of digital modulation signals (4PAM, BPSK, QPSK, 8PSK, 2FSK, 4FSK).

6.Results and Discussion

In this section, the Monte Carlo simulation is used to test the performance of digital signal recognition based on using AR model to extract the spectral line frequency, the digital signals are: 2FSK, 4FSK, 2PSK, 4PSK, 8PSK, 4PAM signals, do simulation 1000 times for every kind of modulation signals. The noise is the white noise, the simulation result shows that the average recognition rate can reach to 95%, the simulation result is just as Figure 4 showing.

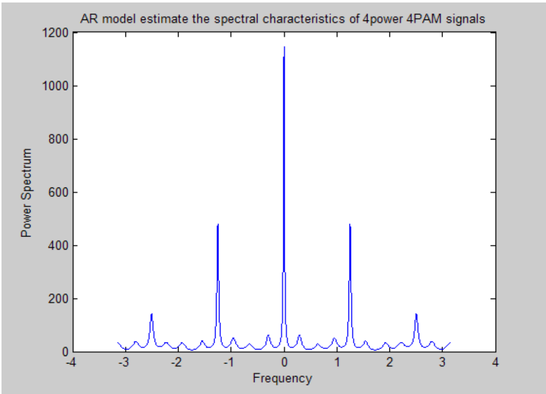

Figure 3. Use AR Model to Estimate the Spectral Characteristics of 4 Power 4PAM Signals

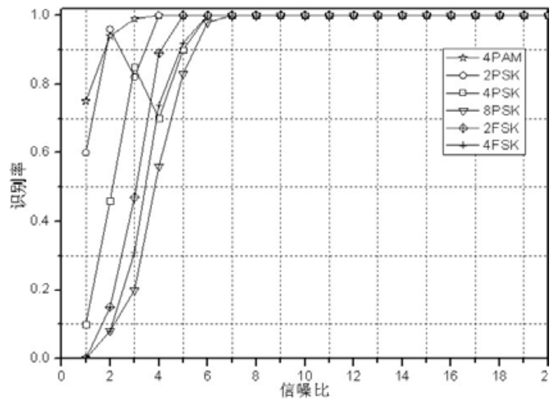

Figure 4. Recognition Rate Under Different SNR

7. Conclusion

In this paper, a modulation signal recognition method is proposed which uses AR model to extract the spectral frequency characteristics of nonlinear transformed digital modulation signals. In this method, the spectral lines frequency of nonlinear transformed signals is chosen as the characteristic parameters, we use the HOYW equations to estimate its frequency depending on the AR model. Compared with other modulation recognition methods, its computational complexity is low, with a higher recognition rate, this method take the characteristics of signals modeling, so it is easier to extract the signals' characteristics in the non-ideal situation, and this feature appears a strong robustness. However, there is relative limitation in the method proposed in this paper, more and more modulation styles, next, we will deeply study and extract other parameters as the modulation recognition feature.

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