Nonlinear Transform CMA for Underwater Acoustic Channel under Impulsive Noise Environment

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Abstract. The traditional constant modulus algorithm (CMA) can't ensure robust convergence performance under impulsive noise environment, hereby a blind equalization by CMA with nonlinear transformation carrying on the received signal was proposed. The impulsive noise can be suppressed effectively by sine transform, in which the linear interval factor and the scale factor are set to keep the scatter plot of the output consistent with the send signal. By embedding nonlinear transformation in CMA blind equalization, the robust convergence performance can be obtained under the impulsive noise environment. The simulation results under the shallow sea channel show that compared with fractional low order CMA and CMA improved by error nonlinear transforming, the nonlinear transformation CMA has the fastest convergence rate and the lowest steady-state residual error. Meanwhile, the nonlinear transformation CMA has highest convergence ratio under different general signal to noise ratio.

Introduction

So far the sound wave is still effective medium to realize underwater signal propagation. High frequency and long distance transmission of the acoustic wave propagation result in energy losses seriously, so underwater acoustic channel bandwidth is very limited. Single carrier adaptive equalization is an effective technical for overcoming the multipath transmission to improve the quality of underwater acoustic communication. Blind adaptive equalization can compensate and tracking the channel without any training sequence, which can save the underwater acoustic channel bandwidth, thus it has potential value in underwater acoustic communication system [1]. In all kinds of blind equalization algorithm, CMA is widely used for its simple structure and easy to implement [2]. CMA can obtain robust convergence performance if the channel interfered with additive white Gaussian noise. However the ambient shallow sea noise has the typical characteristics of impulsive noise that can be described by the $\alpha-$stable distribution. The $\alpha-$stable distribution has no more than $\alpha-$order moments, so CMA is difficult to obtain robust convergence performance for it using the high-order moment of the received signal [4]. For the blind equalization under the impulsive noise environment, fractional low-order CMA [5] and the output error nonlinear transform CMA [6] show more robust convergence performance. However fractional low-order CMA is still a gradient descent algorithm based on minimum dispersion criterion, which can suppress the impulsive noise at cost of loss of high-order moment information of the received signal, as a result, the convergence rate is slow. The output error nonlinear transform CMA can only suppress the impulsive noise in the output error and the robust convergence performance is not ideal, especially when the large step size is adopted. Based on the analysis of impulsive noise characteristics and the gradient descent algorithm iterative process, a nonlinear transform CMA was proposed which the nonlinear transform is carried on the received signal. The nonlinear transform is designed according to sine transform, in which the linear scale factor and amplitude factor are used to keep the scatterplot is consistent before and after transform, and the impulsive noise can be suppressed at the same time. The simulation results under the shallow sea underwater acoustic channel show that the proposed algorithm has robust convergence performance with faster convergence rate and lower steady state

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residual error compared with fractional low-order CMA and the output error nonlinear transform CMA, and it also can obtain higher convergence rate in different generalized SNR.

The impulsive noise model

The engineering practice shows that, the noise in the wireless communication channel often has short-term amplitude pulse, which cannot be simple to be described by Gaussian distribution with exponential trails, but to be suitable to be described by non-Gaussian distribution with algebraic trails, such as the electromagnetic noise, the tropical shallow sea ambient noise and the noise in the city wireless mobile communication channel etc. The distribution of impulsive noise in the channel is close to Gaussian distribution, but has the thick trails characteristics. The $\alpha-$stable distribution is very suitable for describing the statistical characteristics of the impulsive noise. Nikias first studied the application of the symmetric alpha-stable distribution ($S\alpha S$) from the point of view of the statistical signal processing [7], and he proved Gaussian distribution is a special case of $S\alpha S$. Most of impulsive noise can be described by $S\alpha S$. $S\alpha S$ has no closed analytical expressions, and it can only be defined by the characteristic function [8] which can be given by

$$\varphi(t)=\begin{cases}\exp\left\{jat-\gamma|t|^{\alpha}\left[1+j\beta\,\mathrm{sgn}(t)\tan\left(\frac{\alpha\pi}{2}\right)\right]\right\} & \alpha\neq 1\\ \exp\left\{jat-\gamma|t|^{\alpha}\left[1+j\beta\,\mathrm{sgn}(t)\frac{2}{\pi}\lg|t|\right]\right\} & \alpha=1\end{cases} \tag{1}$$

where α （$0<\alpha\leq 2$）is the characteristic exponent which controls the degree of the impulsive noise of the stochastic process, and it decide the shape of the $\alpha-$stable distribution. β （$-1\leq\beta\leq 1$）is the symmetry coefficient. The $\alpha-$stable distribution degenerates to the Gaussian distribution if $\beta=0$ and $\alpha=2$. $a\in R$ is the location parameter which describes the mean values or the median value of the $\alpha-$stable distribution. $\gamma>0$ is the coefficient of dispersion which describes the degree of deviation relative to a of the distribution. In 2004, Chitre through the experiment to determine the tropical shallow sea ambient noise to meet the $S\alpha S$ with $1.5\leq\alpha\leq 1.6$, which show that it has practical meaning to study the blind equalization algorithm under impulsive noise environment for underwater acoustic communication. The typical waveform of impulsive noise is shown in Fig.1, where $\alpha=1.6$.

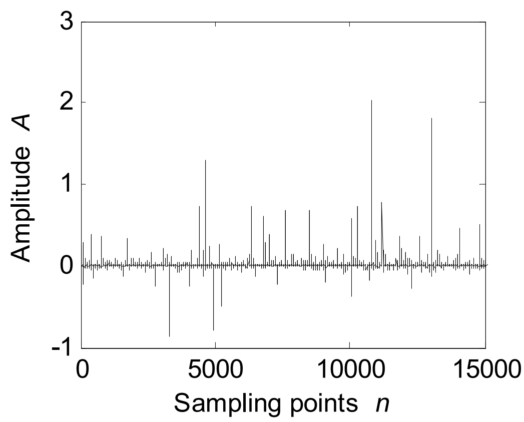

Fig.1 The typical impulsive noise

Nonlinear transform CMA

The equivalent baseband model of CMA is shown in Fig.2. The send signal $x(n)$ transmits through the channel $h(n)$ interfered with the noise $n(n)$, and then the observed signal $y(n)$ is obtained. The objective of blind equalization is to recover the send signal without the information of the send signal and the channel. The equalizer $w(n)$ compensates and tracks the channel characteristics to eliminate the inter-symbol interference (ISI) caused by multi-path transmission. CMA is a special case of the Sato algorithm, which the cost function is designed according to the nonlinear transform of the output of the equalizer. The ideal equalizer result can be obtained by minimize the cost function of CMA.

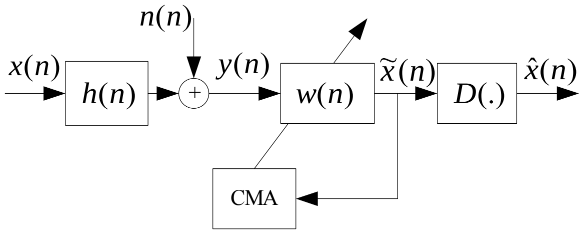

Fig.2 The baseband model of CMA

The cost function of CMA [10] is given by

$$J_{CMA}(n)=\frac{1}{2}E\left[(\left|\tilde{x}(n)\right|^2-R_2)^2\right] \quad (2)$$

where R_2 is the constant modulus of the send signal which can be given by

$$R_2=\frac{E\left[\left|\tilde{x}(n)\right|^4\right]}{E\left[\left|\tilde{x}(n)\right|^2\right]} \quad (3)$$

The equalizer can be updated according to the stochastic gradient descent algorithm [11] which is given by

$$w(n+1)=w(n)+\mu\times\frac{\partial J_{CMA}(n)}{\partial w(n)} \quad (4)$$

where μ is the study step. Let the error function $e(n)$ is

$$e(n)=R_2-\left|\tilde{x}(n)\right|^2 \quad (5)$$

then the updating formula of the equalizer can be given by

$$w(n+1)=w(n)+\mu e(n)\tilde{x}(n)y^*(n) \quad (6)$$

If the noise $n(n)$ meets the Gaussian distribution, CMA can obtain robust convergence performance, especially using the fractionally spaced equalizer, CMA can obtain preferable performance under low SNR. However CMA meets failure convergence when the noise is the impulsive noise meets the $S\alpha S$. According to the signal transmission process, the equalizer output can be given by

$$\tilde{x}(n)=w^H(n)y(n) \quad (7)$$

Then the cost function of CMA can be rewritten as

$$J_{CMA}(n)=\frac{1}{2}E\left[(\left|w^H(n)y(n)\right|^2-R_2)^2\right] \quad (8)$$

The nonlinear transform is carried on the received signal as follow

$$z(n)=\phi(y(n)) \quad (9)$$

Then the cost function of the nonlinear transform CMA can be given by

$$J_{NCMA}(n)=\frac{1}{2}E\left[(\left|w^H(n)z(n)\right|^2-R_2)^2\right] \quad (10)$$

Blind equalization implements ideal equalization by minimizing the cost function, in order to ensure the relationship as follow

$$\min J_{CMA}(n)\Leftrightarrow\min J_{NCMA}(n) \quad (11)$$

The nonlinear transform function needs to meet the two conditions as follow: $\phi(y(n))*y(n)>0$; $\phi(y(n))\propto y(n)$. The condition (1) is to ensure that the symbol characteristics remain the same before and after the nonlinear transform. The condition (2) is to ensure that the gradient direction for the equalizer updating remain the same based on the cost function as Eq.2 and Eq.10.

Here we design the nonlinear transform function according to sine transform. Let

$$f(t)=\sin(t) \quad t\in[-\pi/2,\pi/2] \tag{12}$$

Obviously, $f(t)$ is a monotonic function in the definition domain $t\in[-\pi/2,\pi/2]$. Meanwhile $f(t)$ meets the condition (1) and (2). But the received signal often beyond the definition domain as Eq.12, here a linear scale factor a is adopted to expand the definition domain. Meanwhile the codomain of $f(t)$ is $[-1,1]$, so the amplitude factor A is adopted to expand the codomain of $f(t)$ to meet the characteristics of the transmission signal in the communication system. Thus the nonlinear transform function can be given by

$$f(t)=A\sin(at) \tag{13}$$

where the linear scale factor a and the amplitude factor A can be designed according to the modulate method and the received signal. For example, if the linear scale factor $a=0.5$, the monotonic domain of $f(t)$ can be expand to $[-\pi,\pi]$.

Computer simulation

The shallow sea underwater acoustic channel model [12] is used in the simulation, which has high precision and after lots of the sea experiments. The carrier frequency is 10Hz. the bandwidth of the channel is 2kHz. The send signal adopts QPSK modulation. The signal transmission baud rate is 1000byte/s and the wind speed is 20knot/h. The receiver and the transmitter are located in the water under the 10m and the transmission distance is 10km. The model of channel impulse response can be given by

$$h(t)=\sum_{i=1}^{\infty}a_i p(t-\tau_i) \tag{14}$$

where a_i is the normalized pressure amplitude of the i-th path of the channel. τ_i is the delay of the i-th path relative to the direct path. $p(t)$ is the raised cosine pulse with the roll-off factor is 0.2. The energy of the sound wave decays with the several reflections during the signal propagation process in seawater. Here only the transmission paths which the normalized pressure amplitude larger than 10% is taken into account. The eigenray parameters of the channel are shown in Tab.1.

Tab.1 Eigenray parameters of the shallow sea underwater acoustic channel

Ray number	relative time delay（ms）	Normalized amplitude	Ray number	relative time delay（ms）	Normalized amplitude
1	0.000	1.0000	6	0.120	-0.3286
2	0.013	-1.0000	7	0.120	-0.1080
3	0.013	-0.3286	8	0.210	0.1080
4	0.050	0.3286	9	0.210	0.1080
5	0.050	0.3286	10	0.330	-0.1080

The impulsive noise and Gaussian noise is different, and the impulsive noise cannot be measured by the SNR. Here general SNR (GSNR) is used to measure the impulsive noise in the transmission signal [13] is given by

$$GSNR=10\lg|x(n)|^2/\gamma \tag{15}$$

where $|x(n)|^2$ is the energy of the send signal and γ is the coefficient of dispersion of $S\alpha S$. In the simulation $\alpha=1.6$. The performance of the blind equalization is compared in term of the residual ISI which is given by

$$ISI=\frac{\sum_i |C_i|^2-|C_i|_{\max}^2}{|C_i|_{\max}^2} \tag{16}$$

where C is the combined impulse response of the channel and the equalizer.

In the simulations, the fractional low-order CMA (FC-CMA) and the output error nonlinear transform CMA (ET-CMA) are done for comparison. The nonlinear transform CMA (CT-CMA) proposed in this paper use the parameters as follow: $a = 0.95$ and $A = 1.2$. The length of the equalizer is 42 and the study step size $\mu = 0.0008$. The ISI convergence curve after 500 time's Monte Carlo simulations is shown in Fig.3.

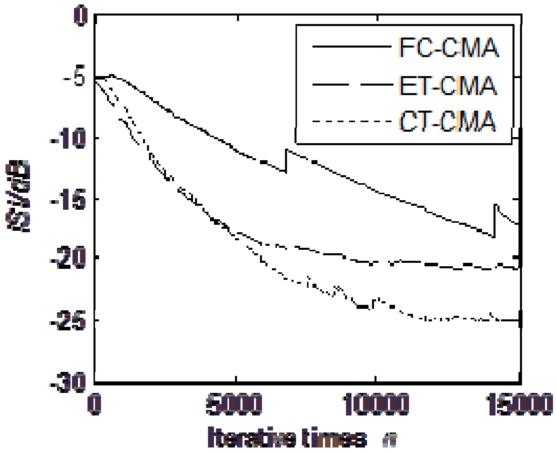

Fig.3 The convergence curve of ISI

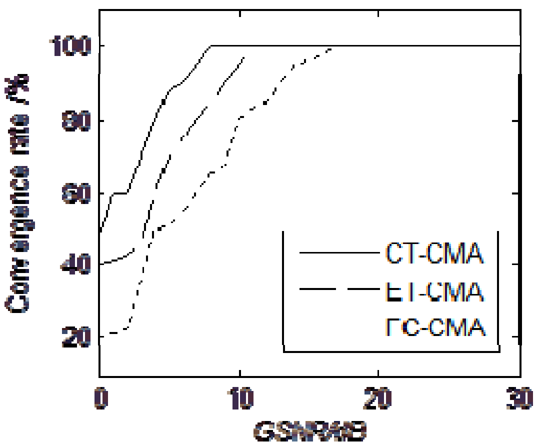

Fig.4The convergence rate

To further verify the performance of CT-CMA, the convergence rate under different GSNR is compared by 500 time's Monte Carlo simulations. The convergence rate is defined the percentage of the residual ISI is lower than -15dB in the simulations and the comparison result is shown in Fig.4. Fig.3 shows that CT-CMA has the fastest convergence rate and the lowest residual steady state error among three algorithms. Fig.4 shows that CT-CMA has highest convergence rate which can prove the robust convergence performance of CT-CMA.

Conclusion

This work proposes a nonlinear transform CMA to solve the blind equalization problem under impulsive noise interference. The nonlinear transform is designed according to sine transform and carried on the received signal, which can suppress the impulsive noise effectively to obtain robust convergence performance. In the simulations, the fractional low-order CMA and the output error nonlinear transform are done for comparison and the results show the effectiveness of the proposed algorithm. The impulse noise is representative in underwater acoustic channel, so this work has practical application significance

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References

[1] Ning Xiaoling, Liu Zhong, Luo Yasong ,Gong, Li, Fu Xuezhi. Improved super-exponential iteration blind equalization algorithm for carrier phase recovery in underwater acoustic channels [J]. Xi'an Dianzi Keji Daxue Xuebao/Journal of Xidian University, 2012, 39(1): 151-156.

[2] Di XueJing, Tong Cheng, Zhang Xia et al. Adaptive step-size constant-modulus algorithm for high-speed optical coherent communication system [J]. Acta Optical Sinica, 2012, 32(10): 1006004.

[3] Xie, Ning ; Hu, Hengyun ; Wang, Hui. A new hybrid blind equalization algorithm with steady-state performance analysis [J]. Digital Signal Processing: A Review Journal, 2012, 22(2): 233-237.

[4] Zhang Yinbing, Zhao Junwei, Guo Yecai, et al. Adapative error-constrained constant modulus algorithm for blind equalization to make it suitable in -stable noise [J]. Journal of Northwestern Polytechnical University, 2010, 28(2): 202-206.

[5] Guo Ying, Qiu Tianshuang, Tang Hong, et al., 2009. Constant modulus algorithm for blind equalization under impulsive noise environments. Journal on Communications, 30(4): 35-40.

[6] Li Jinming, Zhao Junwei, Guo Yecai, et al. A novel robust constant modulus blind equalization algorithm in heavy-tailed noise environment [J]. Applied Acoustics, 2010, 29(1): 17-22.

[7] NIKIAS C L, SHAO M. Signal processing with alpha-stable distribution and application [J]. New York: John Wiley&Sons, Inc 1995.

[8] Tang Hong, Qiu Tian-shuang. Convergence properties of the GCMA in Alpha stable noise environment [J]. ACTA Electronica Sinica, 2009, 37(1): 118-121.

[9] Hwang, Kyuho; Choi, Sooyong. Blind equalizer for constant-modulus signals based on Gaussian process regression [J]. Signal Processing, 2012, 92(6): 1397-1403.

[10] Ozen, A.; Kaya, I.; Soysal, B. A supervised constant modulus algorithm for blind equalization[J]. Wireless Personal Communications, 2012,62(1): 151-166.

[11] Neves, Aline; Panazio, Cristiano. A class of channels resulting in Ill-convergence for CMA in decision feedback equalizers [J]. IEEE Transactions on Signal Processing, 2010,58(11): 5736-5743.

[12] M. Chitre, J. Potter, Ong Sim Heng. Underwater acoustic channel characterization for medium-range shallow water communications [C]. Proceedings of MTTS/IEEE TECHNO-OCEANS'04 conference, 2004, 1: 9-12.

[13] Li, S.; Song, L.-M.; Qiu, T.-S. Steady-state and tracking analysis of fractional lower-order constant modulus algorithm [J]. Circuits, Systems, and Signal Processing, 2011,30(6): 1275-1288.

[14] Zhou, Jun; Liu, Peng; Cao, Suzhi ; Lin, Baojun. Improved variable step-size dithered signed-error constant modulus algorithm [J]. Yi Qi Yi Biao Xue Bao/Chinese Journal of Scientific Instrument, 2011, 32(3): 701-706.