Investigation of SNR Estimation Algorithms of FM Signal for the Underwater Acoustic Channel

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***Abstract*—SNR (Signal to Noise Ratio) estimation is a very important parameter for channel estimation of the communication system. In this paper, some SNR estimation methods of digital modulation system are applied and improved in FM modulation system. Then we summarize several SNR estimation methods (EHM (Envelope High order Moment method), SE (Spectrum Estimation method), FD (Frequency Domain method), EMV (Envelope Mean Variance method), M2M4 (Second order and Fourth order Moment method)). Furthermore, according to the characteristics of FM modulation system, we put forward the improvement of M2M4 and also discuss the optimal algorithm for underwater acoustic Rayleigh channel, Rician channel and Bellhop channel by comparing these methods.**

***Index Terms*—SNR estimation, Rayleigh channel, Rician channel, Bellhop channel**

I. INTRODUCTION

SNR estimation is very important in modern communication system, it is often seen as a parameter of channel quality, the accurate estimation of SNR can improve channel demodulating ability in frequency modulation communication [1] EHM, SE, FD, EMV and M2M4 are considered to be the centralized SNR estimation methods.

EHM (Envelope High order Moment method) applies the fourth order cumulant characteristics of channel statistical process to separate signal energy and noise energy, it can obtain a parameter related to SNR, then, it calculates SNR estimation value based on the relationship between the parameter and SNR [2]. However, the hardware implementation of estimating SNR through the parameter is very difficult for the algorithm's complexity, so this method is not ideal for application in underwater acoustic channel.

SE (Spectrum Estimation method) considers noise power spectrum as stationary, the main idea is to regard the minimum amplitude square of received signal's DFT as the amplitude square of noise's DFT, thus it estimates noise power [3]. Due to the complexity of underwater acoustic channel, the noise could not be seen as stationary power spectrum, this algorithm can not be applied to underwater acoustic channel.

FD (Frequency Domain method) gets approximate original signal sequence and noise sequence from the sampled received signal and measured noise, then performs the DFT of these sequences to estimate SNR [4]. Firstly, this algorithm needs a large number of training sequences, secondly, the accuracy of measured noise which could not be guaranteed in practical underwater acoustic channel has a great influence of SNR estimation, therefore this algorithm is inapplicable in underwater acoustic channel.

EVM (Envelope Mean Variance method) considers the mean square and variance of the received signal envelope as signal power and noise power to estimate SNR [5]. Because of the low estimation accuracy and the poor monotonicity stability of this algorithm in complicated environment channel, it is not suitable for underwater acoustic channel.

M2M4 (Second order and Fourth order Moment method) estimates SNR through the second order and fourth order moment operation of received signal as well as the channel characteristic coefficients [6], it is an adaptive algorithm and has an relatively good stability, hence it is available for underwater acoustic channel, however, this algorithm has some shortcomings, in this paper, we revise M2M4 by analyzing the characteristics of both FM modulation system and underwater acoustic channel, in order to improve performance stability and estimation accuracy of the algorithm in underwater acoustic channel.

This paper is organized as follows. An outline of introduction and improvement of M2M4 is given in Section II. Section III is devoted to dealing with the simulation and verification of these SNR estimation algorithms, in this part, we talk about the system framework and introduce three channel models to simulate underwater acoustic environment, at the same time, some experimental results are summarized in this section. Then Section IV presents the conclusions.

II. INTRODUCTION AND IMPROVEMENT OF M2M4

A. Introduction of M2M4

M2M4 is an adaptive algorithm of estimating SNR through second order and fourth order moment operation based on the characteristics of modulation system, the main idea is as follow [6]:

Make s(t) be the original signal and v(t) be noise, then the received signal is:

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

M2, M4 are second order and fourth order moment of received signal r, when signal and noise are independent, there are following results:

$$\begin{aligned} M_2 &= E\left[r \cdot r^*\right] \\ &= E\left[|s|^2\right] + E\left[|v|^2\right] \\ &= P_s + P_v \end{aligned} \tag{2}$$

$$\begin{aligned} M_4 &= E\left[\left(r \cdot r^*\right)^2\right] \\ &= E\left[|s|^4 + |v|^4\right] + 4E\left[|s|^2 |v|^2\right] \\ &\quad + E\left[\left(s \cdot v^*\right)^2 + \left(s^* \cdot v\right)^2\right] \\ &= \mathrm{k}_s P_s + 4P_s P_v + \mathrm{k}_v P_v \end{aligned} \tag{3}$$

Where E[] denotes expectation, * denotes conjugate operation, | | denotes absolute value operation. Ps, Pv represent the power of signal and noise. Ks, Kv represent the kurtosis coefficient of signal and noise, they are equal to fourth order central moment divided by square of second order central moment of the signal and noise, the kurtosis coefficients Ks, Kv are constant and change with modulation mode and channel.

Then the estimates of signal power and noise power are:

$$P_s = \frac{M_2(\mathrm{k}_v - 2) \pm \sqrt{(4 - \mathrm{k}_s \mathrm{k}_v) M_2^2 + M_4(\mathrm{k}_s + \mathrm{k}_v - 4)}}{\mathrm{k}_s + \mathrm{k}_v - 4}$$

$$P_v = M_2 - P_s \tag{4}$$

Hence the estimated SNR is:

$$\hat{SNR}_{dB} = 10\lg(P_s / P_\mathrm{v}) \tag{5}$$

B. Improvement of M2M4

M2M4 is typically used for digital modulation system in Additive White Gaussian Noise channel, when it is applied for FM signal in underwater acoustic channel, some parameters need to make corresponding change, in addition, the direct application of this algorithm has a performance stability which is not good enough. Therefore, according to characteristics of FM modulation system and underwater acoustic channel, we put forward the improvement of M2M4 in this paper.

Signal even order central moment is related to the distribution of signal, among them, second order central moment reflects the kurtosis of distribution, fourth order central moment reflects the sharpness of distribution. For signal that is satisfied with a specified statistical characteristic, the kurtosis coefficient is constant related to signal statistical distribution [7]. Since FM signal and underwater acoustic channel noise meet some statistical characteristics, this paper takes sample statistics analysis method. We obtain the sample statistics by calculating the value of fourth order central moment divided by square of second order central moment of sample signals to get kurtosis coefficient.

Through simulation analysis of FM sample signals, we obtain the FM sample statistics, then we get Ks is about 1.5 (It is 1.5 on average based on the statistics). By setting Rician, Rayleigh, Bellhop channel parameters to simulate underwater acoustic environment and analyzing the simulation of the channel noise characteristics, in the same way, we get Kv is about 2.3, 2.8, 3.7 (They are 2.3, 2.8, 3.7 on average based on the statistics) for underwater acoustic Rician channel, Rayleigh channel, Bellhop channel in this paper.

According to the above data, the estimated SNR_1 of M2M4 is:

$$SNR_1 = 10\lg(P_s / P_\mathrm{v}) \tag{6}$$

Let SNR_2 be:

$$SNR_2 = 10\lg(\Omega_s / \Omega_\mathrm{v}) \tag{7}$$

Where Ωs, Ωv are mean square and variance of received signal r:

$$\begin{aligned} \Omega_s &= [E(r)]^2 \\ \Omega_v &= \mathrm{var}(r) = E(r^2) - [E(r)]^2 \end{aligned} \tag{8}$$

SNR_2 could indicate the general situation of SNR, therefore, to compensate the estimated SNR of M2M4 with SNR_2 can increase the accuracy and stability of the algorithm. At the same time, since SNR estimation deviation of M2M4 are influenced by modulation method, we give SNR estimation the kurtosis coefficient percentage compensation which is related to the modulation mode and the channel type. For FM system Ks is about 1.5. And Kv is about 2.3, 2.8, 3.7 for underwater acoustic Rician channel, Rayleigh channel, Bellhop channel in this paper.

Then the estimated SNR of improved M2M4 is:

$$\hat{SNR}_{dB} = 10\lg(P_s / P_\mathrm{v}) + \frac{k_s k_\mathrm{v}}{100} \Delta_{dB} \tag{9}$$

$$\text{where } \Delta_{dB} = SNR_1 - SNR_2 \tag{10}$$

III. Simulation and Verification

A. System Framework

In this article, the same period of audio signal passes through the FM modulation system where the carrier frequency is 25k Hz and the sampling frequency is 200k Hz. Besides, we simulate the SNR estimation of received FM signal via the statistical models Rician fading channel (analog deep-sea underwater acoustic environment) and Rayleigh fading channel (analog neritic underwater acoustic environment) to test feasibility of the system. Then we use Bellhop channel to validate performance of these SNR estimation algorithms.

This paper does not concentrate on the accurate evaluation of SNR estimation, but the general evaluation magnitude. In addition, considering Spearman rank correlation coefficient plays a more important role for the later processing of FM modulation system, we set SNR range as [5 dB, 35 dB] and regard Spearman rank correlation coefficient as the main index, use the secondary indexes Pearson's correlation coefficient and NMSE (Normalized Mean Square Error) to compare the performance of these algorithms. The system framework is present in Fig. 1.

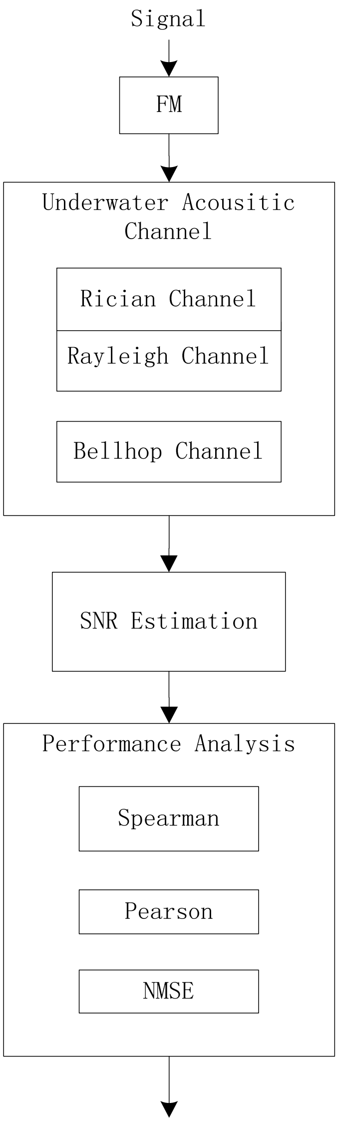

Fig. 1: System Framework

The formulas of these performance indexes are as follows:

$$\text{NMSE}(\rho)=\frac{E\left[(\hat{\rho}-\rho)^2\right]}{\rho^2} \tag{11}$$

Where $\hat{\rho}$ denotes the estimation of ρ .

Pearson's correlation coefficient could be calculated by the following equation:

$$\text{Pearson}_{XY}=\frac{E(XY)-E(X)E(Y)}{\sqrt{E(X^2)-E^2(X)}\sqrt{E(Y^2)-E^2(Y)}} \tag{12}$$

Spearman rank correlation coefficient is the Pearson's correlation coefficient of rank. Assume that the original data x_i, y_i have been ranked in order and make x_i^*, y_i^* be corresponding positions of the ranked data of x_i, y_i. Then x_i^*, y_i^* are called rank of x_i, y_i. The difference of rank d_i can be expressed as:

$$d_i = x_i^* - y_i^* \tag{13}$$

If there exists no same rank, Spearman rank correlation coefficient can be calculated by the following equation:

$$\text{Spearman}_{XY}=1-\frac{6\sum d_i^2}{n(n^2-1)} \tag{14}$$

Where n is the number of data.

If there exist the same rank, the same value in the ranked data must have the same rank, so take the average of corresponding locations as this same rank. Then Spearman rank correlation coefficient could be calculated by the following equation:

$$\text{Spearman}_{XY}=\frac{\sum(x_i^*-E(x^*))(y_i^*-E(y^*))}{\sqrt{\sum(x_i^*-E(x^*))^2\sum(y_i^*-E(y^*))^2}} \tag{15}$$

The range of Pearson's correlation coefficient and Spearman rank correlation coefficient is [-1, 1]. The sign of Pearson's correlation coefficient and Spearman rank correlation coefficient indicates the connection direction between X and Y. If Y increases with the increase of X, the sign is positive, conversely, it is negative. In addition, along with X and Y become more and more close to linearity function relation, the numerical value of Pearson's correlation coefficient becomes more and more large [8]. Along with X and Y become more and more close to strictly monotonicity function relation, the numerical value of Spearman rank correlation coefficient becomes more and more large [9].

B. Channel Models

In this paper, we use Rician fading channel and Rayleigh fading channel to simulate deep-sea and neritic underwater acoustic environment to test feasibility of the system. Then we use Bellhop channel to simulate sea environment to validate the performance.

- *a. Rician channel and Rayleigh channel*

Rician fading channel and Rayleigh fading channel are multipath fading channel models. The multipath fading channel model is as follow:

$$y(t)=\sum_{k=1}^{N(t)} h_k(t)x(t-\zeta_k) \tag{16}$$

Where x(t) is the original signal, y(t) is the received signal via the multipath fading channel, N is the amount of delay spread, $h_k(t)$ denotes the multipath fading which has Rician or Rayleigh distribution in this article, ζ_k denotes the multipath delay.

Then the diagram of this multipath fading channel model could be expressed in the following figure (where Δ in Fig. 2 denotes the measurement interval of the multipath delay):

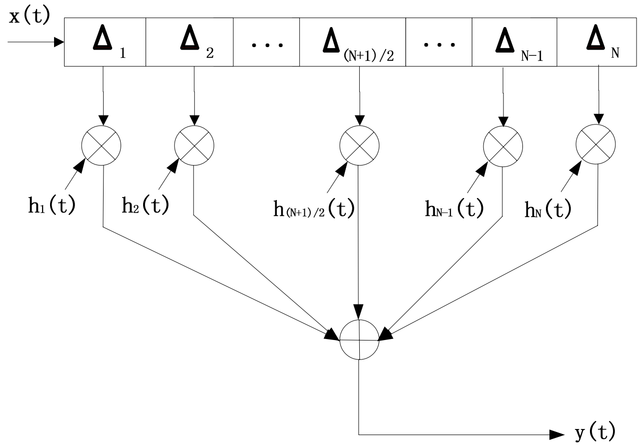

Fig. 2: Multipath Fading Channel Model

When the signal is via the channel, we can obtain received signal from reflection, refraction, scattering, etc multiple paths. And the envelope of received signal has Rayleigh distribution and the phase of received signal has $0 \sim 2\pi$ uniform distribution, then this channel is called Rayleigh fading channel.

When the Signal is via the channel, we can obtain received signal from the following ways: the signals through reflection, refraction, scattering, etc multiple paths as well as the direct signal from transmitter to receiver, then the envelope of received signal obeys Rician distribution, and this channel is called Rician fading channel.

The one-dimensional envelope distribution of the stationary narrow-band Gaussian process which has mean zero and variance σ^2 is Rayleigh distribution. The probability density function of Rayleigh distribution is expressed as [[**10**]:

$$f(r) = \frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right), \qquad r \ge 0 \tag{17}$$

The probability density function of Rician distribution is expressed as [11]:

$$f(r) = \frac{r}{\sigma^2}\exp\left(-\frac{r^2 + A^2}{2\sigma^2}\right)I_0\left(\frac{rA}{\sigma^2}\right), \qquad r \ge 0 \tag{18}$$

Where $I_0()$ is the first kind of zeroth order Bessel function, A and σ are decided by the Rician fading factor K.

$$A = \sqrt{K/(K+1)}$$
$$\sigma = 1/\sqrt{2(K+1)} \tag{19}$$

Where K represents the ratio of line-of-sight propagation energy and other multipath signal energy, and when K = 0 it becomes Rayleigh channel. As underwater acoustic channel has large transmission delay and transmission attenuation, we set Rician fading channel model in this paper as K = 6, the number of multiple paths is 20, the relative speed of terminal is 545 km/h, besides, the rest multipath parameters are shown in Table I.

For Rayleigh fading channel model, K is 0 and the other multipath parameters are the same as Rician model: the number of multiple paths is also 20, the relative speed of terminal is also 545 km/h, in addition, the rest multipath parameters are the same as shown in Table I.

TABLE I.
PARAMETERS OF RICIAN AND RAYLEIGH CHANNEL

Path	Path Delay (ms)	Average Path Gain (dB)
1	0	0
2	50	-10
3	100	-20
4	150	-30
5	250	-40
6	300	-50
7	350	-60
8	400	-70
9	450	-85
10	500	-100
11	600	-120
12	680	-130
13	780	-145
14	880	-165
15	980	-180
16	1080	-200
17	1180	-220
18	1280	-240
19	1380	-260
20	1480	-280

▪ *b. Bellhop channel*

The oceanic medium together with the surface and seabed boundary result in the complicated characteristics of underwater acoustic channel, considering the principal contradiction of actual communication problems and combining reasonable hypothesis and approximation, underwater acoustic channel model is constructed with the mathematical tools to describe the propagation characteristics in oceanic environment. According to different solution methods of the wave equation, underwater acoustic communication models could be roughly divided into five kinds: Ray theory models, Normal mode models, Parabolic equation models, Fast-field models and Multipath expansion models.

Among these models, Ray theory models are suitable for processing the relatively high frequency signal and easy to deal with the channel horizontal distribution problems. The engineering application of Ray theory models is simple and the physical image of these models to describe sound field is clear, besides, the eigenrays' feature information has important reference value and it is easy to deal with the influence on eigenrays caused by the change of environmental parameters. Therefore, Ray theory methods are efficient with a relatively small amount of calculation as well as an excellent practical application value. However, the conventional Ray theory models have some disadvantage, the Bellhop model based on Ray theory models makes the improvement [12].

Bellhop model applies Gaussian approximation to deal with energy caustic, the typical ocean acoustic problem of a point source in a cylindrically symmetric waveguide with depth-dependent sound speed, etc problems, in addition, Gaussian beam technology is not limited to the horizontal layered medium, it is also applied to the condition that source has certain directivity, so this model is suitable for the propagation in complicated underwater acoustic environment. The basic idea of Gaussian beam tracing method is associating the Gaussian intensity distribution with each ray. This ray is the central ray of Gaussian rays, it could have relatively smooth transition to the acoustic shadows and also could smoothly go through the caustics. The results of Bellhop model are more consistent with the results of full wave model. The theoretical principle is given in the following content [13].

The central ray of the beam obeys standard ray equations. The ray equations in first-order form are as follows:

$$\begin{cases} \dfrac{dr}{ds} = c\rho(s) \\ \dfrac{d\rho}{ds} = -\dfrac{1}{c^2}\dfrac{\partial c}{\partial r} \\ \dfrac{dz}{ds} = c\zeta(s) \\ \dfrac{d\zeta}{ds} = -\dfrac{1}{c^2}\dfrac{\partial c}{\partial z} \end{cases} \tag{20}$$

Where r is the horizontal range, z is the depth coordinate, s is the arc length, c is the sound speed, [ρ(s), ζ (s)] denotes the auxiliary variable which is proportional to the local tangent vector.

Then the constraint quantities p(s) and q(s) are introduced to control the energy distribution of Gaussian rays, they are defined as:

$$\begin{cases} \dfrac{dq}{ds} = c(s)\,p(s) \\ \dfrac{dp}{ds} = -\dfrac{c_{nn}}{c^2(s)}q(s) \end{cases} \tag{21}$$

Where c_{nn} denotes the second normal derivative of the sound speed, and it may be computed as the following equation:

$$\begin{aligned} c_{nn} &= c_{rr}\left(\frac{dr}{dn}\right)^2 + 2c_{rz}\left(\frac{dr}{dn}\right)\left(\frac{dz}{dn}\right) + c_{zz}\left(\frac{dz}{dn}\right)^2 \\ &= c_{rr}\left(N_{(r)}\right)^2 + 2c_{rz}\left(N_{(r)}\right)\left(N_{(z)}\right) + c_{zz}\left(N_{(z)}\right)^2 \end{aligned} \tag{22}$$

Where (N(r), N(z)) is a unit normal given by the following equation:

$$\begin{aligned} \left(N_{(r)}, N_{(z)}\right) &= \left(\frac{dz}{ds}, -\frac{dr}{ds}\right) \\ &= c(s)[\zeta(s), -\rho(s)] \end{aligned} \tag{23}$$

Then the beam could be defined as follow:

$$u(s,n) = \mathrm{A}\sqrt{\frac{c(s)}{rq(s)}}\exp\left(-iw\left\{\tau(s) + 0.5\left(\frac{p(s)}{q(s)}\right)n^2\right\}\right) \tag{24}$$

Where A is an arbitrary constant, n is the normal distance from central ray, ω is the angular frequency of source, τ(s) is the phase delay that satisfies the following condition:

$$\frac{d\tau}{ds} = \frac{1}{c(s)} \tag{25}$$

To control the central ray of beam, the initial conditions for the system of four ordinary differential equations are as follow:

$$\begin{cases} \left[r(0), z(0)\right] = \left(r_s, z_s\right) \\ \left[\rho(0), \zeta(0)\right] = \dfrac{(\cos\alpha, \sin\alpha)}{c(0)} \end{cases} \tag{26}$$

Where (r_s, z_s) denotes source location, α is a prescribed takeoff angle.

Then the functions are defined as follow to discuss the p-q initial conditions:

$$\begin{cases} L(s) = \sqrt{-\dfrac{2}{\omega \operatorname{Im}\left[\dfrac{p(s)}{q(s)}\right]}} \\ K(s) = -c(s)\operatorname{Re}\left[\dfrac{p(s)}{q(s)}\right] \end{cases} \tag{27}$$

Where L(s) is the beam radius and K(s) is the beam curvature. Thus the initial conditions are related to L(s) and K(s). Then the initial value q(0) is set to an imaginary constant of magnitude ∈, p(0) is set to one without loss of generality.

$$\begin{cases} q(0) = i\in \\ p(0) = 1 \end{cases} \tag{28}$$

The saddle point method yields the high-frequency asymptotic approximation as follow:

$$u(\alpha_0) \sim A(\alpha_0)c_0\sqrt{\frac{2\pi}{q(0)\omega rR}}\exp\left(-\frac{i\omega R}{c_0} - \frac{i\pi}{4}\right) \tag{29}$$

Where α0 is the angle to receiver, r is the (r,z) cylindrical coordinate of receiver, R is the slant range to receiver.

Then one may match to the exact solution for a point source is shown in the following formula:

$$u(R)=\frac{\exp\left(-\frac{i\omega R}{c_0}\right)}{R} \tag{30}$$

Evidently if there is the condition given by the following equation (31), the forms will match.

$$A(\alpha)=\frac{1}{c_0}\exp\left(\frac{i\pi}{4}\right)\sqrt{\frac{q(0)\omega\cos\alpha}{2\pi}} \tag{31}$$

So the beam field could be constructed according to the following formula:

$$u(\alpha_0)=\sum\delta\alpha\left(\frac{1}{c_0}\right)\exp\left(\frac{i\pi}{4}\right)\sqrt{\frac{q(0)\omega\cos\alpha}{2\pi}}\times\sqrt{\frac{c(s)}{rq(s)}}\exp\left\{-i\omega\left[\tau+0.5\left(\frac{p}{q}\right)n^2\right]\right\} \tag{32}$$

Where δα denotes the differential for the angle of adjacent rays.

TABLE II
PARAMETERS OF BELLHOP CHANNEL

Parameter	Value
Water Depth	100m
Center Frequency	20k Hz
Sampling Frequency	300k Hz
Doppler Spread	500Hz
Source Depth	20m
Receiver Depth	20m
Number of Source Depth	1
Number of Receiver Depth	1
Minimum Range of Receiver	80m
Maximum Range of Receiver	800m
Distance between Source and Receiver	800m
Illuvialhorizon Thickness	20m
Surface Roughness RMS	2m
Top interface of layer Roughness RMS	0
Surface Reflection coefficient	0.46
Bottom Reflection coefficient	0.86
Water Sound Speed	1800m/s
Water Density	$1.7g/cm^3$
Water Attenuation	0.2dB/m
Seabed Sound Speed	1900m/s
Seabed Density	$1.85g/\ cm^3$
Seabed Attenuation	0.25dB/m
Number of Reflection terms	10

Bellhop model describes the sound field in terms of the acoustic line. Every acoustic line from source to receiver goes through the certain path and all received acoustic lines compose the sound field of receiver. The acoustic line length denotes the propagation distance of acoustic wave, the time of acoustic line denotes the propagation time of acoustic wave and the energy of acoustic beam denotes the propagation energy of acoustic wave.

In this paper, the parameter settings of Bellhop model are shown in Table II, and the diagram of Bellhop acoustic line is shown in Fig. 3.

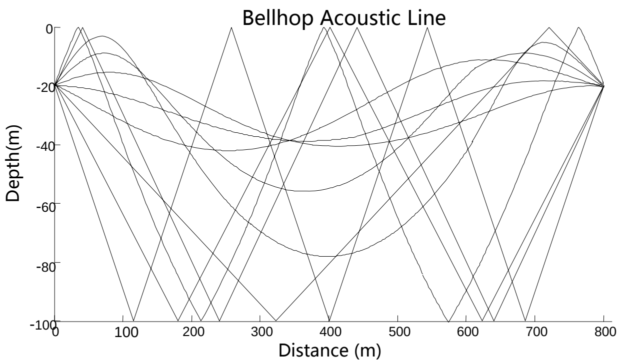

Fig. 3: Diagram of Bellhop Acoustic line

C. *Analysis of Simulation Results*

Figure 4 describes the SNR curves in Bellhop channel. The top half describes the ideal SNR curve and the estimated SNR curve of M2M4, the bottom half describes the ideal SNR curve and the estimated SNR curve of improved M2M4. According to the results, we come to the conclusion: compared with the original algorithm, the estimated SNR curve of improved M2M4 is closer to the ideal SNR curve.

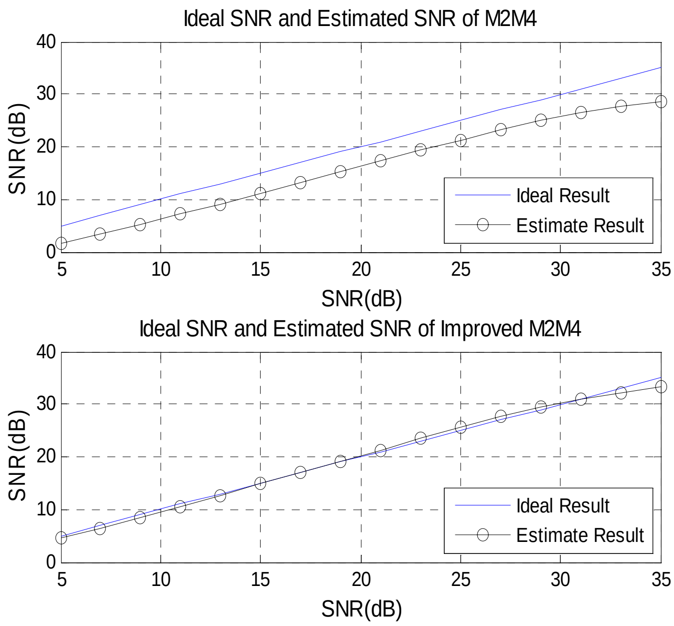

Fig. 4: SNR curves of M2M4 and Improved M2M4 in Bellhop channel

Figure 5 and Figure 7 present the time domain content and the frequency domain content of LFM signal and received LFM signal via different channels. We can acquaint some frequency selective fading characteristics of Rician channel, Rayleigh channel and Bellhop channel in this paper. For the sake of lacking the direct signal from transmitter to receiver, Rayleigh fading channel has more serious signal attenuation compared with Rician fading channel.

Figure 6 and Figure 8 present the histograms of Spearman rank correlation coefficient in Rayleigh fading channel and Rician fading channel. We can easily compare the basic situation of these SNR estimation algorithms in underwater acoustic channel statistical models Rician channel and Rayleigh channel. Ignoring SE and FD which are not suitable for underwater acoustic channel for the sake of reasons mentioned in previous article, the improved M2M4 is the best.

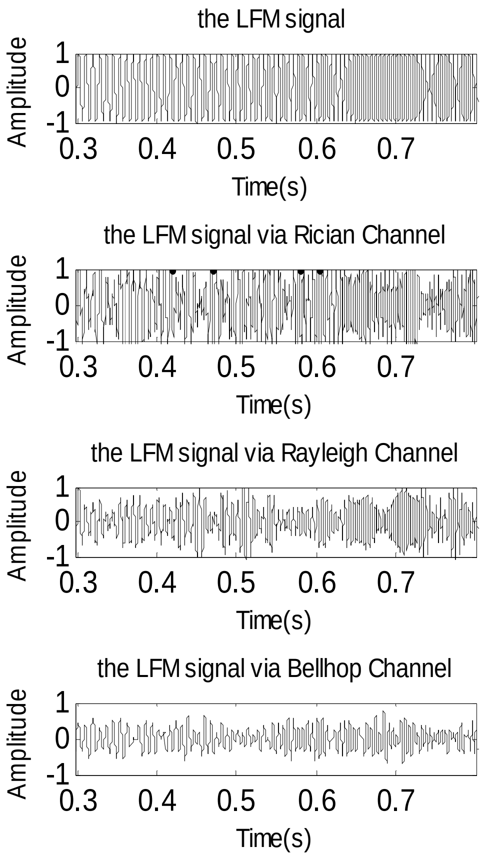

Fig. 5: the Time domain content of LFM signal and Received LFM signal via the channel when SNR is 5dB

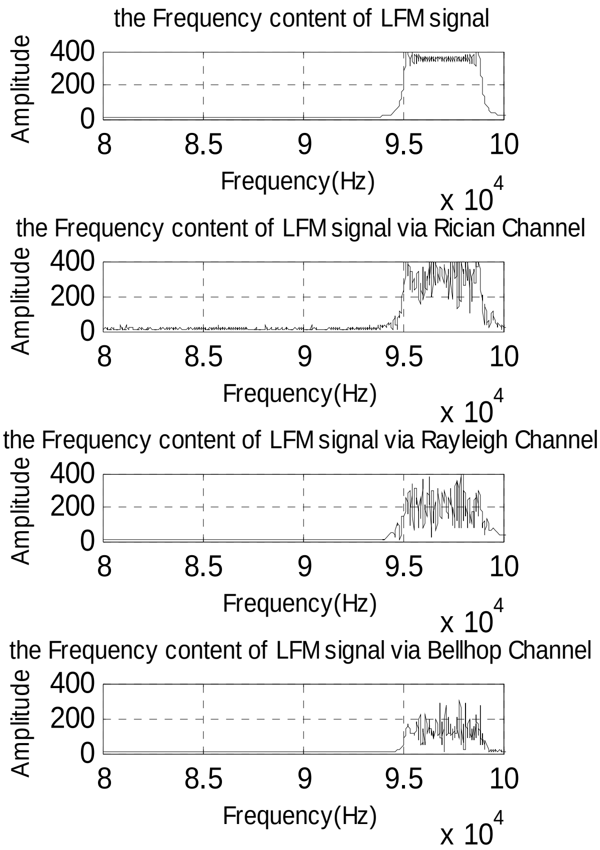

Fig. 7: the Frequency domain content of LFM signal and Received LFM signal via the channel when SNR is 5dB

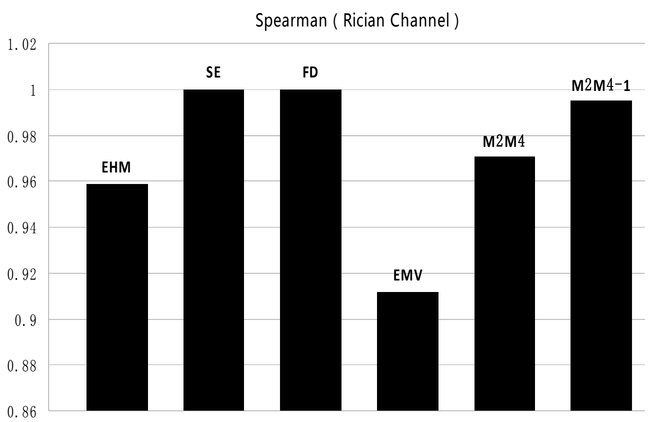

Fig. 6: Histogram of Spearman rank correlation coefficient in Rician channel
(M2M4-1 represents the Improved M2M4)

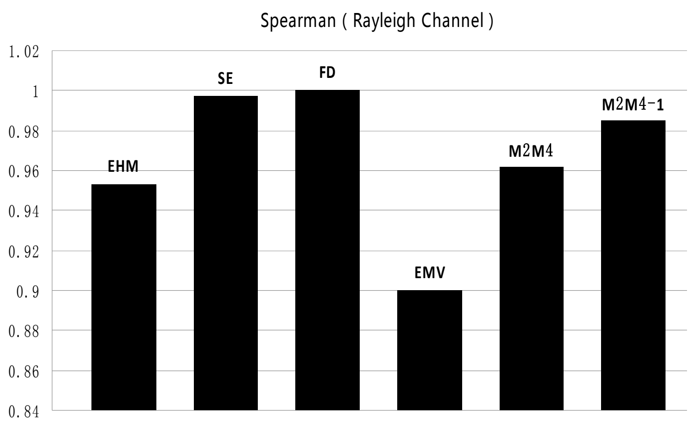

Fig. 8: Histogram of Spearman rank correlation coefficient in Rayleigh channel
(M2M4-1 represents the Improved M2M4)

TABLE III:
PERFORMANCE INDEXES OF SNR ESTIMATION ALGORITHMS IN THREE KINDS OF CHANNELS

	Performance Indexes		
Algorithms	Rician channel		
	Spearman	Pearson	NMSE
EHM	0.9588	0.9481	0.1605
SE	1.0000	0.9555	2.8629
FD	1.0000	0.9992	0.0638
EVM	0.9118	0.9116	0.0512
M2M4	0.9706	0.9394	0.0416
M2M4-1	0.9951	0.9571	0.0369
Algorithms	Rayleigh channel		
	Spearman	Pearson	NMSE
EHM	0.9532	0.9467	0.2002
SE	0.9971	0.9570	2.4909
FD	1.0000	0.9994	0.0469
EVM	0.9000	0.9150	0.0665
M2M4	0.9618	0.9445	0.3966
M2M4-1	0.9853	0.9665	0.1302
Algorithms	Bellhop channel		
	Spearman	Pearson	NMSE
EHM	0.9996	0.9835	0.2721
SE	0.9998	0.9137	5.2988
FD	1.0000	0.9996	0.0899
EVM	0.9995	0.9813	0.1069
M2M4	0.9998	0.9973	0.0943
M2M4-1	1.0000	0.9980	0.0015

(M2M4-1 represents the Improved M2M4)

Comprehensively analyzing the data, we come to the conclusions. Compared with the original algorithm, considering monotonicity, linearity and NMSE, the performance of improved M2M4 is developed, among them, the Spearman rank correlation coefficient has about two percent increase. The Spearman rank correlation coefficient implies the monotonicity performance of these algorithms (A>B means A is better than B): FD > Improved M2M4 > EHM > EMV. The Pearson's correlation coefficient implies the linearity performance of these algorithms: FD > Improved M2M4 > EHM > EMV.

Analyzing the statistical models of underwater acoustic channel, compared with Rician channel, the signal attenuation of Rayleigh channel is more serious, as a result, the SNR estimation performances including monotonicity and NMSE are worse than Rician channel.

IV. Conclusion

Since Spearman rank correlation coefficient plays a more important role for the later processing of FM system, we regard Spearman rank correlation coefficient as the main index and synthesize other indexes to analyze the SNR estimation methods. The results of Rician channel, Rayleigh channel and Bellhop channel suggest M2M4 is the optimal algorithm for underwater acoustic channel, this algorithm can adapt well to the complicated environment channels. Moreover, the performance stability and estimation accuracy of improved M2M4 have significant development which makes the improved M2M4 more adaptable in complicated underwater acoustic channel.

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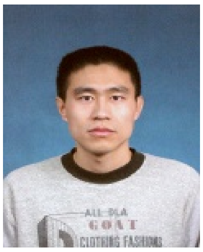

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