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Research on Satellite Communication Channel Estimation and Adaptive Modulation Decision Technology

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Abstract: Satellite communication has become a modern indispensable means of communication. In order to reduce the BER in a maximum limit, the transmitting terminal of adaptive satellite communication technology can automatic select working frequency, data transmission rate and modulation mode. In this study, a simple and practical design of system based on the Signal-to-noise Ratio (SNR) estimation scheme with adaptive modulation for satellite communication is presented. This system applies Maximum-likelihood (ML) algorithm to estimate SNR. Simulation deduces the modulation mode switching threshold. In addition, the adaptive modulation switching threshold is the trade off between spectral efficiency and Bit Error Rate (BER). Furthermore, the modulation mode decision strategy should be considered to achieve the highest spectral efficiency and to maintain constant average BER. The design of an integrated SNR estimation and adaptive modulation mode decision system is highly challenging. Numerical results show that the design fulfills superior performance.

Key words: Satellite adaptive communication, ML SNR estimation algorithm, spectral efficiency, bit error rate, adaptive modulation decision

INTRODUCTION

As the development of satellite communication, the interference of satellites has become a serious problem. Adaptive satellite communication technology is proposed to weaken the satellites interference and to solve problems that different satellites communication systems were unable to exchange information.

Compared with the traditional system of communication satellites, the mode of adaptive communication system is no longer fixed, unchanging. For example, highly efficient modulation mode and high data rate are used in ideal channel situations, low efficiency modulation mode is transmitted when the SNR is low (Holm and Geir, 2003).

SNR estimation of cellular and satellite communication system is indispensable. On one hand, Signal-to-noise Ratio (SNR) estimation provides switching, power control (Chen *et al*., 2011; Okaniwa, 2012) and required channel quality information of channel allocation algorithm, on the other hand, it can adaptively provide a more effective demodulation algorithm to improve the demodulation performance.

L'opez-Valcarce and Mosquera (2007), Gao and Tepedelenlioglu (2005), Gappmair *et al*. (2007), Gappmair *et al*. (2009), Gappmair (2008), Gappmair *et al*. (2007) and Chen and Beaulieu (2005) proposed a variety of SNR estimation methods which are divided as Data-aided (DA) and None-data-aided (NDA) estimators. DA estimators need to launch a dedicated signal before detection data, such as leading character. Compared with DA estimators, NDA estimators do not have to meet the requirement, so the applicability is more extensive.

Based on the SNR estimated results, the decision of which modulation mode to use is made by assigning switching thresholds $s_1, s_2, \ldots s_N$, N modes. The switching thresholds are obtained under the constraint of specific target BER (Hole and Qien, 2001).

In this part, the determination of the modulation-mode switching for the constant-power adaptive modulation scheme is contrived. Webb and Steele (1995) used each constituent modulation mode's BER curve to find SNR values which met the target BER requirement of each modulation mode. Seiichi and Hiroshi (2007) and Ibrahim *et al*. (2007) have used the switching levels since then. Considering the balance of BER and spectral efficiency, modulation mode decision strategy is developed to achieve the highest possible spectral efficiency, under a constant average BER.

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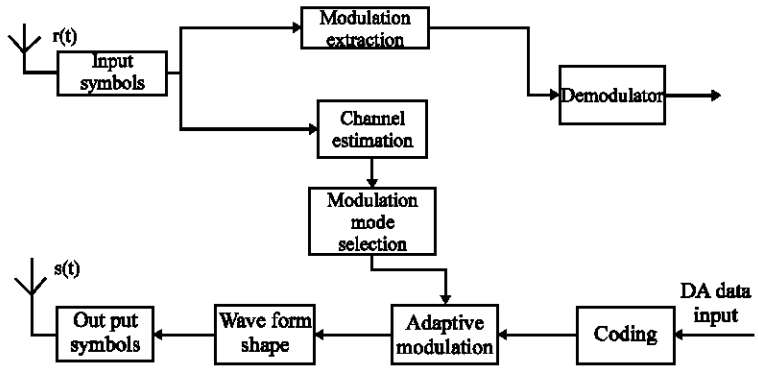

Fig. 1: Modulation mode decision strategy based on the SNR estimation system model

The block diagram of modulation mode decision strategy based on the SNR estimation system in this study is illustrated in Fig. 1.

CHANNEL ESTIMATION ALGORITHM

In this study, two SNR estimators applied for AWGN channel among those above estimators were selected, Maximum-likelihood (ML) Estimator and Second and Fourth Order Moments (M2M4) Estimator. On the basis of the simulation results, we contrast the SNR estimation performances.

ML ESTIMATOR

This SNR estimator, based on ML estimation theory, was introduced by Kerr (1966) and Gagliardi and Thomas (1968). The basic thoughts of maximum likelihood estimation method is to assume that noise is zero mean Gaussian white noise with variance σ2, signal power is Ps. According to joint (Probability Distribution Function) PDF of the received signals, the method aims at solving the max joint PDF of Ps and σ2 estimation, further obtaining the SNR estimation.

According to the system model (Pauluzzi and Beaulieu, 2000), ML RXDA SNR estimator for complex signal can be written as:

$$SNR_{ml} = \frac{S_{ml}}{N_{ml}} = \frac{N_{SS}^2[\frac{1}{K}\sum_{k=0}^{k-1} Re\{r_k^* m_k^{(i)}\}]^2}{\frac{1}{K}\sum_{k=0}^{k-1}|r_k|^2 - N_{SS}[\frac{1}{k}\sum_{k=0}^{k-1} Re\{r_k^* m_k^{(i)}\}]^2} \quad (1)$$

Real signal can be written as:

$$SNR_{ml,real} = \frac{N_{ss}^2[\frac{1}{k}\sum_{k=0}^{K-1} r_k m_k^{(i)}]^2}{\frac{1}{K-3}\sum_{k=0}^{K-1} r_k^2 - \frac{N_{ss}}{K(K-3)}[\sum_{k=0}^{K-1}\{r_k m_k^{(i)}\}]^2} \quad (2)$$

L is signal source length, N_{ss} presents sample rate per symbol $K = LN_{ss}$.

Equation 1 and 2 are real time, replacing the estimated symbol, after pulse-shaped estimated method according to the denoted by TXDA. The estimated method depends on the judgment of receiver after the pulse shape. Estimated values are replaced by the pulse shaping samples from the actual transmission to be the largest likelihood estimated TxDA form. In this study, ML TxDA estimated algorithm programming is applied to achieve signal-to-noise ratio estimation.

M2M4 ESTIMATOR

M2M4 SNR Estimator algorithm is an adaptive algorithm that utilizes the correlation of the second and fourth order moments. Let M_2 denote the second moment of y_n as:

$$\begin{aligned} M_2 &= E[y_n y_n^*] \\ &= SE[|a_n^2|] + \sqrt{SN}E[a_n w_n^*] + \sqrt{SN}E[a_n^* w_n] + NE[|w_n^2|] \end{aligned} \quad (3)$$

And let M_4 denote the fourth moment of y_n as:

$$\begin{aligned} M_4 &= E[(y_n y_n^*)^2] \\ &= S^2E[|a_n|^4] + 2S\sqrt{SN}\cdot E[|a_n|^2 a_n w_n^*] + (E[|a_n|^2 a_n w_n^*] + E[|a_n|^2 a_n^* w_n]) + SN\cdot(E[(a_n w_n^*)^2] \\ &+ 4E[|a_n|^2|w_n|^2] + E[(a_n^* w_n)^2]) + 2N\sqrt{SN}(E[|w_n|^2 a_n w_n^*] + E[|w_n|^2 a_n^* w_n]) + N^2E\{|w_n^4|\} \end{aligned} \quad (4)$$

For any MPSK signal, M2M4 SNR estimator for complex signals can be written as:

$$\hat{SNR}_{complex} = \frac{\sqrt{2M_2^2 - M_4}}{M_2 - \sqrt{2M_2^2 - M_4}} \quad (5)$$

PERFORMANCE INDEX

Estimation performance indexes are used to compare above indicated algorithms.

Standard deviation (STD):

$$\mathrm{STD} = \sqrt{\frac{1}{L}\sum_{i=1}^{L}(\mathrm{SNR} - \mathrm{SNR\_mean})^2} \tag{6}$$

where, L is signal source length.

NMSE and CRB: The "best" SNR estimator is the one that is unbiased and has the smallest variance. The statistical MSE reflects both the bias and the variance of SNR estimate. It is described as:

$$\mathrm{MSE}\{\hat{\rho}\} = E\{(\hat{\rho}_i - \rho)^2\} \tag{7}$$

where, $\hat{\rho}$ is an estimate of the SNR and ρ is the true SNR:

$$\mathrm{MSE}\{\hat{\rho}\} = \frac{1}{N_t}\sum_{i=1}^{N_t}(\hat{\rho}_i - \rho)^2 \tag{8}$$

where, N_t is the number of trials.

The appropriate CRB gives a lower bound for unbiased estimator that means unbiased estimator which variance is less than the lower bound cannot be obtained.

Assuming $\hat{\rho}$ is unbiased, one obtains the CRB for unbiased SNR estimators in complex AWGN channels as:

$$\mathrm{Var}\{\hat{\rho}\} \geq 2\left(\frac{2\rho}{N_{sym}} + \frac{\rho^2}{N_{SS}N_{sym}}\right) \tag{9}$$

CRB for unbiased SNR estimators may be expressed in terms of the normalized MSE:

$$\mathrm{NMSE}\{\hat{\rho}\} = \frac{\mathrm{MSE}\{\hat{\rho}\}}{\rho^2} = \frac{\mathrm{var}\{\hat{\rho}\}}{\rho^2} \geq 2\left(\frac{2}{\rho N_{sym}} + \frac{1}{N_{ss}N_{sym}}\right) \tag{10}$$

ESTIMATION RESULTS

As satellites locate in outer space, the parameter of channel free space part is basically constant and there is no scintillation fading. As a result, the noise is mainly White Gaussian Noise. Channel condition can be stimulated in the AWGN experiment channel environment.

Parameter set: Perfect carrier and symbol timing recovery are assumed, pulse-shaped by a Root Raised-cosine (RRC) filter with roll-off factor $\alpha = 0.5$, $N_{ss} = 16$, Monte Carlo simulation times $N_t = 20$, QPSK modulation signal, the SNR estimation range is [-20,40]dB. The block length L is supposed as L = 128, L = 256, L = 512, L = 1024. Compared with the performances of ML and M2M4 algorithms, results are depicted in Fig. 2.

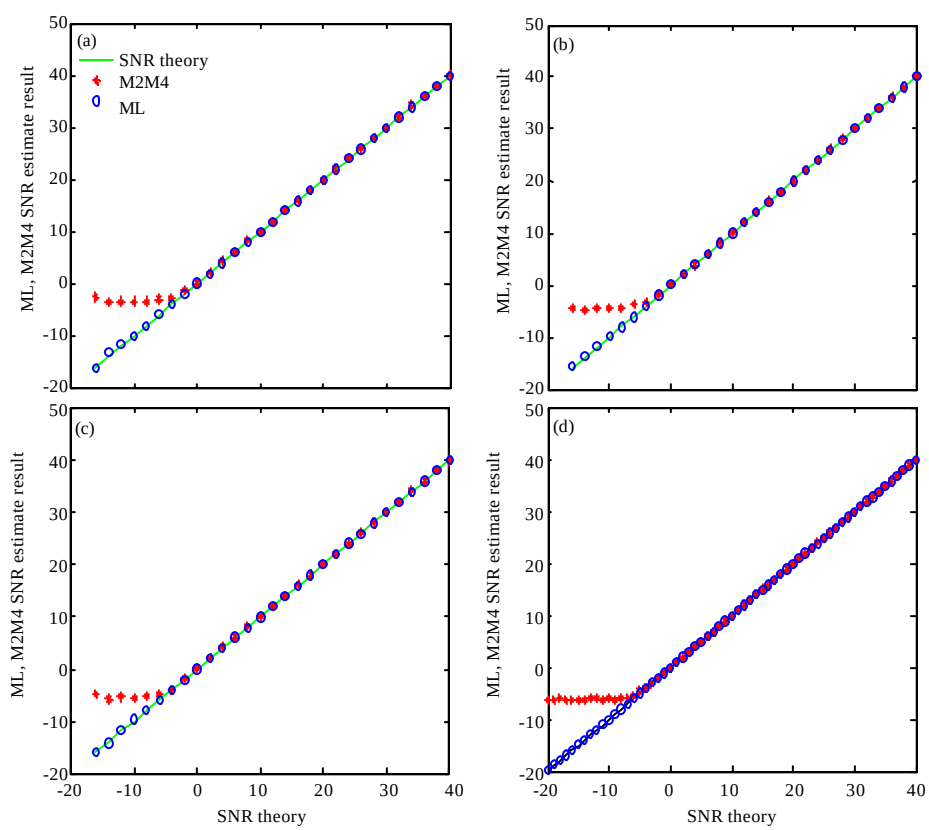

Fig. 2(a-d): Performances of ML and M2M4 under different length block, (a) L = 128, (b) L = 256, (c) L = 512 and (d) L = 1024

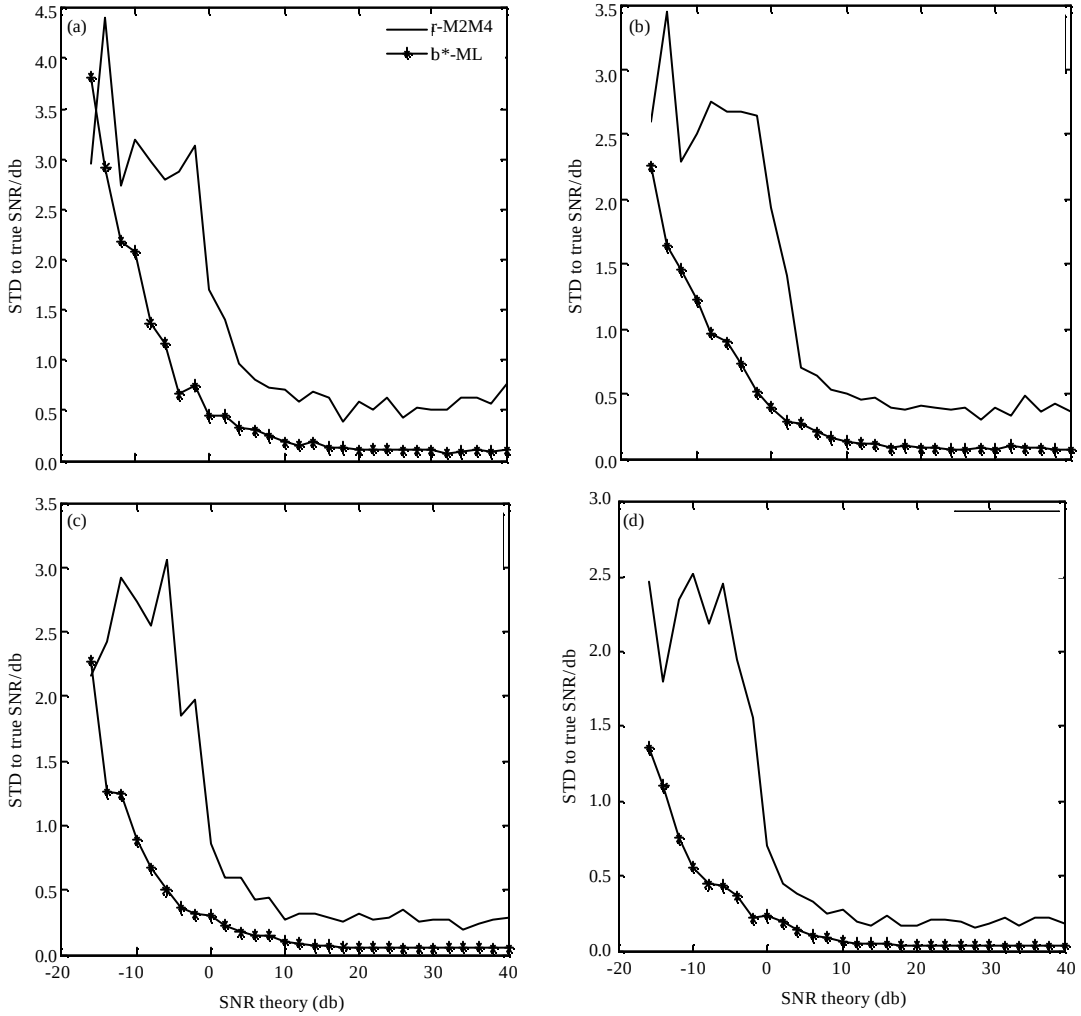

Fig. 3(a-d): STD of the two algorithms under different block length, (a) L = 128, (b) L = 256, (c) 512 and (d) 1024

Based on comparison, ML estimator is completely more efficient at low SNR. M2M4 estimator is asymptotically efficient at high SNR. As ML estimator is based on the truth values of received signal r_k and pulse-shaped m_k, its estimation result is more accurate.

Moreover, STD of two algorithms is considered with true SNR under different lengths of block. In Fig. 3, compared results are presented.

Both algorithms performances are relatively better with the increase of block lengths. The data of STD decreases as the block length increases. It is because more estimated results can be closed to the true SNR values with the growth of data length.

Thirdly, the NMSE result of each estimator related to CRB is plotted as the Monte Carlo simulation times Nt change.

Parameter set: Perfect carrier and symbol timing recovery are assumed, pulse-shaped by the Root Raised-cosine (RRC) filter with roll-off factor $\alpha = 0.5$, QPSK modulation signal, the SNR estimation range is [-20,40]dB. The block length L is1024. Monte Carlo simulation times is supposed as $N_t = 20$ and 100.

Considering the floating rate of MSE, simulation times of Monte Carlo are under 100 between SNR interval [-5,15] dB. The results are depicted in Fig. 4.

RESULTS AND ANALYSIS

- NMSE of two algorithms decreases as N_t increases. The more the repetition times are, the closer NMSE performance comes towards CRB curves

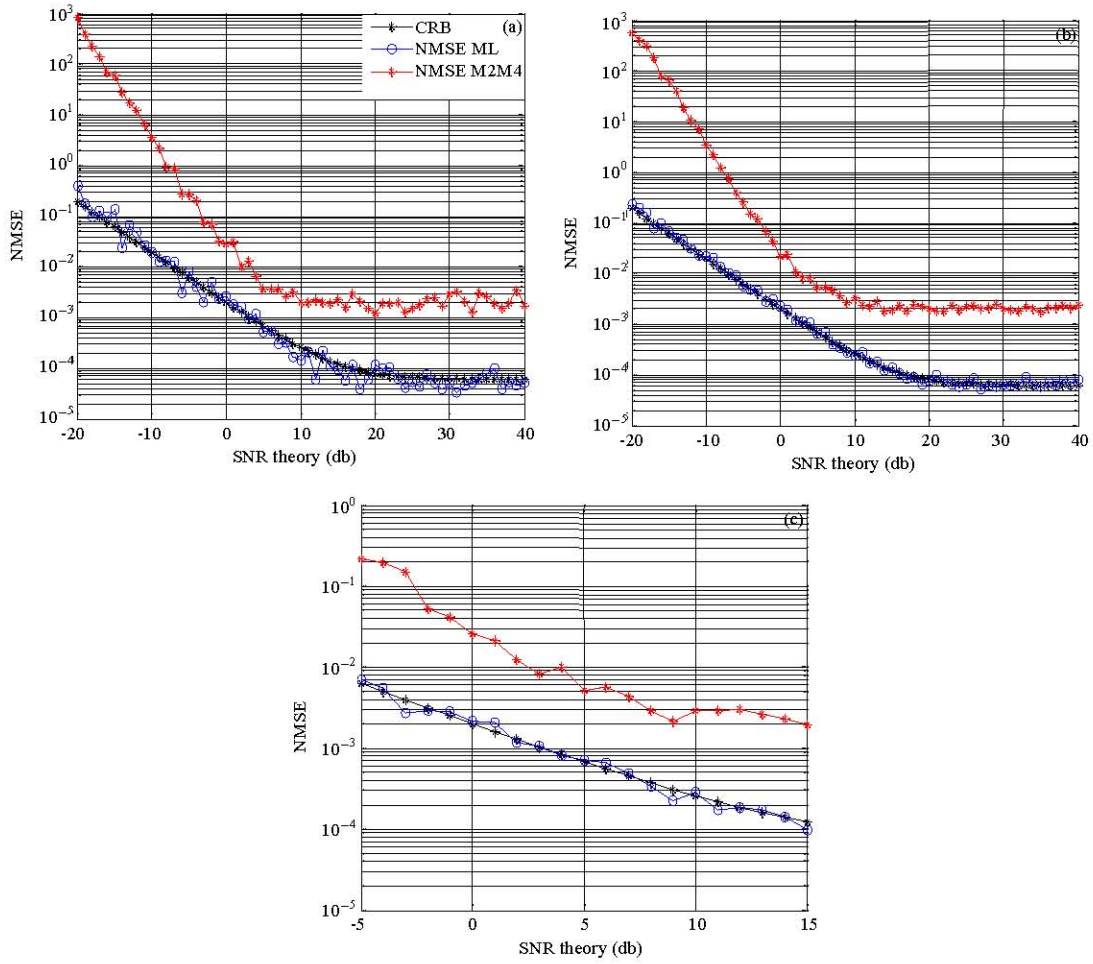

Fig. 4(a-c): MSE of SNR estimation compared to the CRB, (a) $N_t = 20$, (b) $N_t = 100$ and (c) SNR interval [-5, 15] db

- The CRB normalizes to the true SNR, it does not decrease with the increase of SNR, however, it approaches a constant
- The M2M4 estimator is based on higher-order moments, the curves asymptotically approach constant values at high SNR. However, its performance at low SNR becomes relatively worse than that of ML algorithm. Specifically, in the SNR range of [-5,15]dB, NMSE of ML is less than 0.01 dB and approaches to CRB .The NMSE of M2M4 can be controlled within 0.2 dB

ADAPTIVE MODULATION DECISION

Adaptive modulation strategy is the core of adaptive satellite communication. In order to meet the requirements of current channel transmission conditions, modulation strategy requires the change of modulation parameters at any time. The communications modulation mode can be decided by the results of the ML algorithm in free space AWGN channel. Modulation mode conversion guidelines and simulation results are given in the next part.

MODULATION MODE AND FEATURE ANALYSIS OF THE COMMON SATELLITE COMMUNICATION

Channel characteristics of the common satellite communication:

- Limited bandwidth depending on the frequency resources and the propagation characteristics of channel
- Interference and noise impact dramatically
- Power-constrained

The satellite communication channel is a typical band-limited and non-linear, noise is basically white Gaussian noise and the modulation mode mainly can be divided into two broad categories: power-efficient modulation and spectrum-efficient modulation. So, modulation and demodulation techniques in digital satellite communications require high power utilization and spectral efficiency. According to characteristics of satellite communication channel, high spectral efficiency, a strong anti-jamming and anti-fading ability are needed for the modulated signal.

High power-utilization modulation mode should be used in the case of power-constrained satellite communication system and in the band limited system a higher spectral efficiency modulation mode is required. The balance between them should be worked out in actual system design.

In satellite communication systems, there are many modulation methods available, such as MPSK, MQAM, FSK, the larger the M value is, the higher spectral efficiency and power requirements are. Nonlinear characteristics of the channel which is widely used, has a constant envelope modulation. The most representative modes are phase shift keying (BPSK), Quadrature Phase Shift Keying modulation (QPSK) and the derivative methods, such as staggered four-phase phase-shift keying OQPSK (Orthogonal Quadrature Phase Shirt Keying). QPSK is used as the traditional modulation technique for satellite communications which has a narrow bandwidth, high spectral efficiency, strong anti-jamming capability characteristics. With the development of satellites, earth station amplifier linearization and digital modulation techniques progress adapt the new satellite service such as 16QAM, 32QAM, OFDM, TCM.

According to the received signal, the receiver can change the channel (such as fading, interference and noise, etc.) to make accurate estimation and track adaptive modulation conversion decision threshold, inform the transmitter to adjust the modulation mode as well, in adaptive modulation system.

MODULATION MODE SWITCHING THRESHOLD SET

In recent years, there have been several modulation mode conversion criteria, such as building the cost function (Choi *et al*., 2001). The transmission efficiency and reliability of system need to reach equilibrium. Some criteria maintain the premise that certain transmission is reliable and optimize the transmission efficiency.

Under the premise that is maintaining a certain bit error rate, we give priority to anti-noise performance, then the modulation modes which anti-noise performance meet the conditions of higher bandwidth efficiency can be considered. The BER requirements of different communication services will be different. For instance, the voice signal transmission business requires the transmission error rate is generally less than 1%, when transferring the business data signals, the transmission error rate is generally less than 0.01%. So, the corresponding BER door limits are decided by different communication businesses. BER door limits convert into the corresponding modulation signal SNR switching threshold.

WHOLE SYSTEM SIMULATION

This study applies modulation modes commonly used in satellite communications: 2FSK, BPSK, QPSK, 16QAM, the relationship between the BER and SNR is shown in following Table 1.

The capacity of continuous communication channel is well known to be $C = B\log_2(1+r)$ bit/s which r is the SNR. The Probability Density Function (PDF) of the instantaneous channel SNR, r over a fading channel is given as:

$$p(r) = \frac{1}{r} e^{-\frac{r}{\bar{r}}} \tag{11}$$

In a variable transmission rate, constant power communication system, the capacity is depicted as:

$$C = \int_0^{\infty} B\log_2(1+r)p(r)dr \tag{12}$$

Spectral efficiency is defined as C/B. To maximum the adaptive communication system spectral efficiency, we have:

$$\frac{C}{B} = \sum E[\log_2 M_i] = \sum_{i=1}^{N} \log_2 M_i p(s_i \le r < s_{i+1}) \tag{13}$$

M_i is defined as corresponding modulation constellation size. While a switching level s_i belongs to the set $s = \{s_i | i = 0,\ldots N\}$.

Table 1: BER and SNR theory relation table

FSK	BPSK	QPSK	16QAM
$Pe = \frac{1}{2}\mathrm{erfc}(\sqrt{\frac{r}{2}})$	$Pe = \frac{1}{2}\mathrm{erfc}(\sqrt{r})$	$Pe = 1-[1-\frac{1}{2}\mathrm{erfc}(\sqrt{r/2})]^2$	$Pe = \frac{3}{16}\mathrm{erfc}(\sqrt{\frac{r}{10}})$

Table 2: Experiment process test results

SNR-th	1	5	10	12	15	20	21	24
SNR-mean	1.0039	4.9888	10.0566	12.0088	15.0006	20.0072	21.0162	24.0213
Modulation mode	BER is too high	BER is too high	BER is too high	BPSK	QPSK	QPSK	16QAM	16QAM

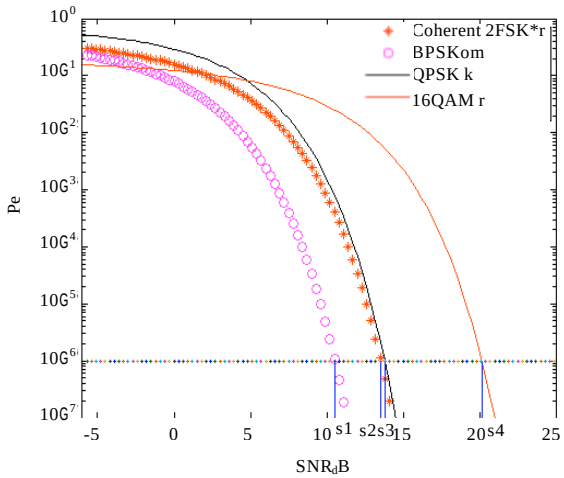

Fig. 5: Modulation modes switching threshold setting

We suppose the modulation set of adaptive modulation mode decision system is {2FSK, BPSK, QPSK, 16QAM}. The least bit error rate which the communication requires is 10^{-6} in this article. The corresponding four modulation mode signal-to-noise ratio switching threshold was set as $\{s_1, s_2, s_3, s_4\}$. In this case, the system adaptive modulation spectral efficiency is derived:

$$\frac{C}{B} = 0P_0 + P_{BPSK} + 2P_{QPSK} + 4P_{16QAM} \tag{14}$$

where, P_0 stands for interrupt probability. Since FSK has the least spectral efficiency among those modulation modes, it has no contribution on the optimized spectral efficiency, in the system. P_{BPSK}, P_{QPSK}, P_{16QAM} represent the possibility that adaptive modulation system adopts the corresponding modulation method.

As BER = 10^{-6} according to Table 1, the threshold (dB) is calculated as followed. $s_1 = 10.5298$; $s_2 = 13.5401$; $s_3 = 13.7891$; $s_4 = 20.1523$. In Fig. 5, modulation modes switching thresholds are presented.

Judgment process is described as followed: choosing any kinds of modulation cannot meet the error rate requirement, when the channel environment is SNR<s_1, the system will not be able to select next signal modulation mode.

When s_1< SNR <s_2, only the BPSK modulation signal attains the communication anti-noise requirement, feedback "BPSK" to the transmitter as the next signal modulation mode.

When $s_2 \leq$ SNR<s_4, both 2FSK and QPSK meet the transmission power requirement, this time the system spectral efficiency should be improved. We prefer to send QPSK modulation to obtain higher system spectral efficiency.

When the SNR >s_4, similarly we select 16QAM to maximize the spectral efficiency, simultaneously maintain the target average BER.

We set [0,25] dB as the range of the estimated value for the signal to noise ratio.

The experiment process test results are shown in the Table 2.

CONCLUSION

This study focuses on the adaptive modulation decision making problem in satellite adaptive communication system. Under Gaussian white noise environment, two algorithms mentioned are compared through simulation by QPSK channel modulation method. The ML algorithm's performance at low signal-to-noise ratio interval is significantly better than that of M2M4 algorithm. In adaptive modulation mode switching criterion research part, an efficient communication system should meet the power utilization ratio and the band utilization rate requirement at the same time. That means better anti-noise performance modulation mode should stand out to meet the communications business BER conditions requirements. When the environment is favorable, the transmit power is not limited. In addition, all the modulation modes meet the needs of BER, so we should consider the modulation mode which spectral efficiency is higher.

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