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), 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 $s_1, s_2, ..., s_N$ N modes. The switching thresholds are obtained under the constraint of specific target BER (Holm 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. Senichi 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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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 $\sigma^2$, signal power is $P_s$. According to joint (Probability Distribution Function) PDF of the received signals, the method aims at solving the max joint PDF of $P_s$ and $\sigma^2$ 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:

$$ SNR_{ML} = \frac{\sum_{k=1}^{K} |\sum_{j=1}^{J} \text{Re}(t[m_k^j])|^2}{N_s} $$

Real signal can be written as:

$$ SNR_{real} = \frac{\sum_{k=1}^{K} |\sum_{j=1}^{J} t[m_k^j]|^2}{N_s} $$

**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:

$$ M_2 = \mathbb{E}[y_n y_n^*] $$

$$ = \mathbb{E}[u_n^2] + 2N_s \mathbb{E}[u_n w_n^*] + |\mathbb{E}[w_n]|^2 + \mathbb{E}[w_n^2] $$

Let $M_4$ denote the fourth moment of $y_n$ as:

$$ M_4 = \mathbb{E}[y_n y_n^* y_n y_n^*] $$

$$ = 8\mathbb{E}[u_n^4] + 24N_s \mathbb{E}[u_n^2 w_n^2] + 8\mathbb{E}[w_n^4] + 8\mathbb{E}[w_n^2 u_n^2] + 8\mathbb{E}[w_n^2 u_n^2] + 8\mathbb{E}[w_n^4] $$

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

$$ SNR_{M2M4} = \frac{\frac{1}{K-1} \sum_{k=1}^{K} |\sum_{j=1}^{J} t[m_k^j]|^2}{N_s} $$

**PERFORMANCE INDEX**

Estimation performance indexes are used to compare above indicated algorithms.
Standard deviation (STD):

\[
\text{STD} = \sqrt{\frac{1}{L} \sum_{i=1}^{L} (\text{SNR} - \text{SNR}_{\text{mean}})^2}
\]  

(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:

\[
\text{MSE}(\hat{\rho}) = E[(\hat{\rho} - \rho)^2]
\]  

(7)

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

\[
\text{MSE}(\hat{\rho}) = \frac{1}{N} \sum_{i=1}^{N} (\hat{\rho}_i - \rho)^2
\]  

(8)

where, \(N\) 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:

\[
\text{CRB} \geq \frac{2\text{Var}(\hat{\rho})}{N}
\]  

(9)

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

\[
\text{NMSE}(\hat{\rho}) = \frac{\text{MSE}(\hat{\rho})}{\rho^2} \geq \frac{2}{\rho N} + \frac{1}{N N_{\text{SNR}}}
\]  

(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 simulated 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 \(\alpha = 0.5\), \(N_u = 16\), Monte Carlo simulation times \(N_i = 20\), 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](image-url)
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 $r_i$ 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 $N_t$ charge.

**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 $L$ is 1024. 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.
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 QOQPSK (Orthogonal Quadrature Phase Shift 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:

\[
P(r) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}r^2}
\]  

(11)

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

\[
C = \int_{0}^{\infty} B \log_2(1+r) p(r) dr
\]  

(12)

Spectral efficiency is defined as \( C/B \). To maximize the adaptive communication system spectral efficiency, we have:

\[
\frac{C}{B} = \sum_{m} E [\log_2 M_j] = \sum_{m} \log_2 M_j \cdot p(r, r < s_m)
\]  

(13)

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

Table 1: BER and SNR theory relation table

<table>
<thead>
<tr>
<th>Modulation</th>
<th>2FSK</th>
<th>BPSK</th>
<th>QPSK</th>
<th>16QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pe = \frac{1}{2} \text{erfc}(\sqrt{3})</td>
<td>Pe = \frac{1}{2} \text{erfc}(\sqrt{6})</td>
<td>Pe = 1 - \frac{1}{2} \text{erfc}(\sqrt{3})</td>
<td>Pe = \frac{1}{16} \text{erfc}(\sqrt{10})</td>
<td></td>
</tr>
</tbody>
</table>

1971
Table 2: Experiment process test results

<table>
<thead>
<tr>
<th>SNR-th</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>12</th>
<th>15</th>
<th>20</th>
<th>21</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation mode</td>
<td>BER is too high</td>
<td>BER is too high</td>
<td>BER is too high</td>
<td>BPSK</td>
<td>QPSK</td>
<td>QPSK</td>
<td>16QAM</td>
<td>16QAM</td>
</tr>
</tbody>
</table>

When \( s_1 < \text{SNR} < s_2 \), only the BPSK modulation signal attains the communication anti-noise requirement, feedback “BPSK” to the transmitter as the next signal modulation mode.

When \( s_2 < \text{SNR} < s_4 \), 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 \([0, 25] \text{dB}\) 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.

**REFERENCES**


