Satellite Channel Markov Model of Ka-band based on Principal Component

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Abstract——With the consideration of the existing Ka-band satellite channel model in data processing method deficiency, the Ka-band satellite channel propagation characteristic is analyzed and the influence of meteorological factors on the satellite channel is discussed. The channel of meteorological factor principal component is obtained by using the principal component analysis and fuzzy clustering analysis method is introduced into channel classification. The Ka-band satellite channel multi-sates Markov model is established and simulated finally. By comparing the level crossing rate and average fade duration with the former. The results shown that this proposed channel model is more accurate and effective and it is significant to the Ka-band satellite communication research.

Index Terms—Ka-Band; Principal Component Analysis; Fuzzy Clustering; Rain Attention; Markov Model

I. INTRODUCTION

With the development demand of satellite communication channel capacity and the more and more crowd of the C, Ku band, it is necessary for the satellite communication system to work in higher frequency band, larger bandwidth, and high spectrum efficiency. The Ka-band satellite communication system with widely bandwidth, large communication capacity, narrow beam, small size of terminal and strong ability of preview the interference will become the inevitable trend of the future satellite communication. For the propagation characteristics of mobile satellite channel, many domestic and foreign organizations have proposed the channel statistical model in the single environment, Its market has become the key point of the international companies. Consequently, more and more researchers have begun to engage in the satellite communication research, more and more countries and institutions have have take part in the development and use of the Ka-band satellite communication system [1, 2]. With the foundation of the former channel model, first of all, we analyze propagation characteristic of Ka-band satellite channel, such as the multipath, rainfall, atmospheric absorption and atmospheric scintillation. Secondly, in view of the channel characteristics of the Ka-band satellite communication, the Ka-band satellite channel multi-state Markov model is established and the performances are simulated based on principal component analysis and fuzzy cluster analysis method.

Figure 1. The modeling idea of the multi-states Markov chain model

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The Fig. 1 is the modeling idea of the multi-states Markov chain model of the Satellite Channel in Ka-band. The results show that this proposed channel model is more accurate and effective than the previous proposed models and it is significant to the satellite communication research.

II. KA-BAND SATELLITE CHANNEL PROPAGATION CHARACTERISTIC ANALYSIS AND ITS MODEL

In the process of signal transmitted from the satellite to earth receiving terminal, the cloud produce the shadow effect, due to reflection and scattering of the buildings, mountains and so on, the multipath effect is serious. The environmental characteristics of channels is shown in Fig. 2. Especially for ka-band satellite signal, due to rainfall and atmospheric absorption, that can produce rain attenuation and gas absorption.

A. Multi-Path Effect

Reflecting, scattering and diffraction caused by multipath effect exists widely in each frequency of satellite communication and that may produce very serious effect on signal [1]. The study have proved that Rice distribution can be used to describe multi-path effect, the amplitude probability density function can be expressed as

$$p_{mic}(r) = \frac{r}{\sigma^2} \exp(-\frac{r^2 + A^2}{2\sigma^2})I_0\left(\frac{Ar}{\sigma^2}\right), r \geq 0$$  

where $I_0$ is the first kind of modified zero order Bessel function. $\sigma^2$ is the value of line of sight (LOS), $A$ is the value of scattering component, $\alpha$ is the power of scattering component, $A = \frac{A^2}{2\sigma^2}$ is the Rice factor.

B. Shadow Effect

Satellite communication experience links is from satellite to earth, the strength of the signal will weaken when it pass away the trees, buildings, and cloud, etc. The study have proved that the Lognormal distribution can be used to describe shadow effect[1], the amplitude and phase of the probability density function can be written as

$$p_{\text{log}}(r) = \frac{1}{2\pi \sqrt{d_o} \delta} \exp\left(-\frac{\ln r - \mu}{2d_o^2}\right)$$  

where $d_o$ and $\mu$ are the standard deviation and mean, respectively.

C. Rainfall Characteristics

Rainfall attenuation effect refers to the influence on signal transmission, it could cause the signal attenuation and absorption. The degree of the rain attenuation is relate to frequency, rainfall rate and other factors. In lower L-band and S-band channel model, it is scarcely consider rainfall attenuation [2], but with the increase of the signal frequency, especially like Ka-band high frequency band communication, rain attenuation may be the main factors caused communication error, therefore we must consider the effect of rain attenuation [3, 4, 5, 6]. The main effects of rain attenuation are absorption, scattering and radiation, the specific description as follows:

Rain Attenuation. The satellite link caused by rainfall can be expressed as

$$A_R = \gamma_R L_R(R, \theta) \text{ (dB)}$$  

where $L_R(R, \theta) \text{ (km)}$ is the the rain layer length of the waves which depends on rainfall rate and elevation. The attenuation $\gamma_R$ (dB/km) can be calculated from the power time law relationship $R$ (mm/h).

$$\gamma_R = kR^\alpha$$  

where $k$ is the value of $k_h$ or $k_v$, $\alpha$ is the value of $\alpha_h$ and $\alpha_v$. As the frequency range from 1 to 1000 GHz.

Rainfall Noise. Electromagnetic wave absorption attenuation caused by rainfall could have influence on earth station, this kind of rainfall noise reduced to receiving antenna input is equivalent to the antenna thermal noise, it has great influence on the received signal to noise ratio. Usually, the higher is the antenna elevation, the smaller is the rainfall effect of noise. Rainfall noise can calculated the following formula.

$$\Delta Tr = (1-10^{-4/10})Tr$$  

where the $A$ denote rainfall attenuation(dB), $Tr$ is the rainfall temperature(270K).

Rainfall to Polarization Effect. General the polarization interference is measured by XPD (cross polarization identification rate) which is that the signals pass through the rain belt, can be calculated by the following formulas.

$$XPD = U-V(f)\log A_R$$  

$$U = C_f + C_c + C_0 + C_s$$  

$$V(f) = \begin{cases} 
12.8 f^{0.19} & 8\text{GHz} \leq f \leq 20\text{GHz} \\
22.6 & 20\text{GHz} \leq f \leq 35\text{GHz} 
\end{cases}$$
where $U$ is the sum of gain in dB. $V(f)$ is the function of $f$, $C_f$ is the frequency factor, $C_r$ is line polarization improvement factor, $C_g$ is geographic gain factor and $C_d$ is raindrop angle factor.

D. Atmospheric Scintillation Characteristics

The so-called scintillation is refers to the rapid signal amplitude and phase fluctuate caused by the wave propagation path on the small irregularities. Tropospheric scintillation happened in Ka-band usually occurs at low elevation ($5^\circ$–$15^\circ$), hot and humid climate conditions of satellite communication system. That will cause the signal attenuation and can be described as

$$X(t) = \ln W(t)$$  \hspace{1cm} (10)

where $W(t)$ is signal instantaneous value. ITU-R has divided the above factors into three categories: slowly varying factors $A_1$, fast varying factors $A_2$, and the middle factor $A_3$ (gas absorption), $A_4$ (cloud attenuation), $X$ (the attention caused by the atmospheric scintillation), the total value of attenuation

$$A_{total} = A_y + (A_n + A + X)^2 + A_o^2$$  \hspace{1cm} (11)

III. KA-BAND SATELLIATE CHANNEL ANALYSIS METHOD BASED ON THE PRINCIPAL COMPONENT

In this paper, we use principal component analysis to get main influence factors on the Ka-band satellite communication system. In some previous researches, the channel was divided into good-state, bad-state or good-state, medium-state, and bad-state, according to their personal experience. These methods were simple and rough and had a lot of problem, such as, whether this state division is reasonable, how to define the above three states and what the standard of the state division is suitable, etc.. This section will give fuzzy clustering analysis method, which contains the state division method of the multi-sate satellite channel in theory [9].

A. Data Standardization

In order to rule out the differences of different data, we need to standardize the four physical quantities in the above. The standardization procedure is shown as follows

$$\hat{x}_{i,j} = \frac{x_{i,j} - \bar{x}_j}{s_j}$$  \hspace{1cm} (13)

where $\bar{x}_j = \frac{1}{n} \sum_{i=1}^{n} x_{i,j}$ is the sample mean of the $j$th variable and $s_j^2 = \frac{1}{n} \sum_{i=1}^{n} (x_{i,j} - \bar{x}_j)^2$ is the variance.

The correlation coefficient matrix of the sample for can be written as

$$R = (r_{ij})_{p \times p}$$  \hspace{1cm} (14)

where $r_{ij} = \frac{1}{n} \sum_{i=1}^{n} x_{i,i} - x_{i,j}$, $i, j = 1, 2, ..., p$

The calculation of the related physical quantity. In the section, we must calculate related physical quantities, such as eigenvalues, eigen vector, variance contribution rate, cumulative variance contribution rate and the extraction of principal component. Assume that $\lambda_1, \lambda_2, ..., \lambda_p$ denote the $p$ eigenvalues and $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_p > 0$, the corresponding eigenvector is $a_1, a_2, ..., a_p$. If the contribution rate of the former $r$ eigenvalues has reach to 85%, we can obtain the former principal component. Principal component scores are the new data of the original data in the new coordinate system defined by principal component

$$Y_j = \sum_{i=1}^{p} a_{ij}x_i$$  \hspace{1cm} (15)

where $j = 1, 2, ..., r$.

IV. FUZZY CLUSTERING METHOD OF KA-BAND SATELLITE CHANNEL

It is the most important to determine the state of Ka-band multi-state satellite channel. In some previous researches, the channel was divided into good-state, bad-state or good-state, medium-state, and bad-state, according to their personal experience. These methods were simple and rough and had a lot of problem, such as, whether this state division is reasonable, how to define the above three states and what the standard of the state division is suitable, etc.. This section will give fuzzy clustering analysis method, which contains the state division method of the multi-sates satellite channel in theory [9].

A. Data Standardization

The key of principal component analysis is to get principal component, its tool is covariance matrix. Because covariance matrix is susceptible to index of the dimension and the order of magnitude, we must make the original data turn into standardization data via some standardization processing.

$$(x_{i,j})_{n \times 5} = \left( x_{11}, x_{12}, x_{13}, x_{14}, x_{15}, \ldots, x_{n1}, x_{n2}, x_{n3}, x_{n4}, x_{n5} \right)$$  \hspace{1cm} (16)

In order to rule out the differences of different data, we need to standardize the four physical quantities in the above. The standardization procedure is shown as follows

Translation-standard. The deviation transform $(x_{i,k})$ represents the characteristic variables

$$(i = 1, 2, \ldots, n; k = 1, 2, 3, 4, 5)$$  \hspace{1cm} (17)
where \( x_i = \frac{1}{n} \sum_{j=1}^{n} \frac{x_{ij} - x_i}{n} \).

**Translation-range transformation.** After the mean value of each variable is 0, the standard deviation is 1, and the influence of dimension has been eliminated, but the \( x_i \) may not be in the interval \([0,1]\). Translation-range transformation

\[
x_i^* = \frac{x_i^* - \min(x_i^*_{min})}{\max(x_i^*_{max}) - \min(x_i^*_{min})} (k = 1, 2, 3, 4, 5) \quad (18)
\]

We can make \( 0 \leq x_i \leq 1 \) now.

**B. Establish Fuzzy Similar Matrix**

The next is the process of establishing fuzzy similar matrix. According to angle cosine method, the elements of similar matrix is written as

\[
r_{ij} = \frac{\sum_{k=1}^{m} x_{ik} \cdot x_{jk}}{\sqrt{\sum_{k=1}^{m} x_{ik}^2 \cdot \sum_{k=1}^{m} x_{jk}^2}} \quad (19)
\]

We can obtain fuzzy similar matrix \( R \) of the LMSC and \( R = (r_{ij})_{n \times n} \).

**C. Dynamic Fuzzy Clustering**

In the fuzzy clustering analysis, it is require that the equivalence matrix should have reflexivity, symmetry and transitivity, but there are only two former properties in the general fuzzy similar matrix. Therefore, we need to reform the fuzzy similar matrix as follow

\[
R \rightarrow R^2 \rightarrow R^3 \rightarrow \cdots \rightarrow R^{2k-1} = R_k \quad (20)
\]

\[
R^2 = R \cdot R = (r_{ij})_{n \times n}, r_{ij} = \frac{m}{i=1} \min(r_{ij}, r_{ji}) \quad (21)
\]

\[
t(R) = R_k = (t_{ij})_{n \times n} \quad (22)
\]

After obtaining the fuzzy equivalence matrix \( t(R) \), we can array the different elements from big to small according to the value order of \( \lambda \) and obtain the dynamic clustering figure of Ka-band.

**V. Multi-States Markov Satellite Channel Model of Ka-Band**

We can obtain the representative Ka-band satellite channel \( n \) states from the above analysis. When the mobile terminal moves along with a certain path, the several channel states will convert mutually. The process can be expressed by the multi-state Markov model. The detail procedure of the Markov model is given by the following steps.

**A. Determination of Every Single State Statistical Model**

According to the fuzzy clustering method, we can get the best clustering number \( n \) of the Ka-band is \( n \). The first state of the LMSC follows the Rayleigh model, the second obeys the Suzuki model, and the third one obeys the Rice model,..., the \( n \)th state obeys the Suzuki distribution. Their respective parameters can be gained from the original data.

**B. Establishment of Ka-Band Satellite Channel Markov Model**

Ka-band satellite channel Markov model can be described as the transition matrix \( P \) and state matrix \( S \). The \( n \) states transition matrix of Markov model is written as

\[
P = (p_{ij})_{n \times n} \quad (23)
\]

\( p_{ij} \) denotes the transition probabilities from the state \( i \) to the state \( j \), and \( \sum_{i=1}^{n} p_{ij} = 1(i=1, \cdots, n) \), the state vector \( S = [s_1, s_2, \cdots, s_n] \). This Markov chain is a periodic, irreducible and normal, so its steady state distribution exists and is equal to the limit distribution, then

\[
S_p = S \quad (24)
\]

**VI. Simulation and Comparison**

In order to validate the validity of Ka-band satellite channel model, the relevant data of Nanjing area was used to simulate the model. Assume that the satellite's height is 35786 km, transmission frequency is 30 GHz, vehicle terminal movement speed for 36 km/h. According to ITU-R related material, we can get the original data of satellite channel.

**Table I. Measured Data**

<table>
<thead>
<tr>
<th>( K )</th>
<th>( A_0 ) (dB)</th>
<th>( A_1 ) (dB)</th>
<th>( A_2 ) (dB)</th>
<th>( \Delta Tr ) (K)</th>
<th>( XPD ) (dB)</th>
<th>( X ) (dB)</th>
<th>( L_{tot} ) (dB)</th>
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<tbody>
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<td>79.58</td>
<td>2.67</td>
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<tr>
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</table>
According to fuzzy clustering method, we can know that the best clustering number of the Ka-band is 3, so the Markov model has three states \( S = \{ s_1, s_2, s_3 \} \). We divide the measured data (signal envelope) into 3 states. The envelop from -5dB to -15dB are \( s_1 \), from -16dB to -26dB are \( s_2 \), from -26dB to -36dB are \( s_3 \). The state series \( S = \{ 2, 2, 2, 1, 3, 3, 1, 1, 2, 2, 3, 1, 3, 1, 2, 2, 2, 3, 1, 2, 3, 2, 1, 2, 3, 3, 1, 1, 3, 2, 3, 3, 2, 1, 2, 1, 1, 3, 2 \} \). The transition matrix \( \text{P} \) and state vector \( \text{S} \) can be got from the state division series.

![State division](image1.png)

![Average fading duration](image2.png)

![Level crossing rate](image3.png)

According to the Matlab simulation of the above parameters, we can get the second order statistics (average fading duration and level crossing rate) and they are shown in Fig. 4 and Fig. 5. The average fading duration (AFD) and level crossing rate (LCR) are the most important indicators of channel properties in satellite channel models. Especially, when the signal level is less than 0 dB [2]. We can perceive that the simulated average fade duration, level crossing rate based on principal component analysis are more agreeable with the measured data than that one’s based on general model. The simulation of principal component analysis Markov model in low level shows better coincide than general Method [10]. The simulations demonstrate that the simulation model is effective. So the principal component analysis Markov model has some realistic meaning.

**VII. SUMMARY**

The Ka-band satellite channel multi state model based on principal component analysis is proposed based on the analysis of Ka-band satellite channel transmission characteristic. The proposed model is better than some previous one. Firstly, the principal component analysis method and fuzzy weighted analysis method are applied to satellite channel modeling. Mathematical modeling method is used to solve some key problems in the channel modeling [7]. Secondly, The influencing factors of satellite channel entire link are considered, such as free space loss, cloud attenuation, rain attenuation, attenuation of tropospheric scintillation. The insufficient of the former models which just consider one or several factors in a model are overcome. Further, the proposed model has strong portability because of the main channel characteristic analysis data are from the ready-made model of ITU-R in this paper, the related data can be calculated according to the local meteorological statistics. Finally, the most important two order statistics(AFD and LCR) of the measure of channel properties are obtained by using the computer simulation, the correction of proposed channel model can be verified by the comparison of simulation results and measured data, and the model’s practical significance can be illustrated.

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