Characteristics Analysis and Modeling of Satellite Mobile MIMO Channel

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Abstract. In recent years, with the rapid growth of satellite communication services, the spectral bandwidth needs to be increased urgently. In the face of the dilemma of limited orbit position and lack of spectrum resources, MIMO technology has been applied to satellite communications to improve the spectrum efficiency and channel capacity, which has become the main research direction, and the modeling of MIMO channel is an indispensable work. This paper firstly analyzes and summarizes the actual measurement work and channel characteristics of the satellite mobile MIMO channel, and on this basis, gives the concrete steps of using two-state Markov chain and taking C.Loo model as the subchannel to build the probability statistical model of satellite mobile MIMO channel. At the same time, according to the model established in this paper, the simulations are carried out in different environments, so as to study the effects of simulation parameters such as simulation environment, cross polarization discrimination and satellite elevation on the performance of satellite mobile MIMO systems.

Keywords: MIMO · Land mobile satellite · Channel model · Probability statistical model

1 Introduction

In recent years, with the rapid growth of satellite communication services, the spectral bandwidth needs to be increased urgently. In the face of the dilemma of limited orbit position and lack of spectrum resources, how to improve the spectrum efficiency and channel capacity of satellite communication systems has become the main research direction. Among them, the most remarkable technical achievement is MIMO (Multiple-Input Multiple-Output) technology, which has epoch-making significance in modern communication technology and is also the key technology of broadband wireless communication in the future [1].

For a satellite mobile MIMO communication system, the satellite mobile MIMO channel as its core is very important. The realization of any MIMO technology is closely related to the characteristics of its underlying MIMO channel. Satellite communication links are different from normal terrestrial MIMO communication systems, and their performance influence factors are also different. For the satellite system with a long communication link, the size of the satellite in the space segment itself is very

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small, and it is not easy to meet the condition that the distance between the antennas exceeds half of the wavelength of the signal. Compared with the terrestrial MIMO system, the distance between the satellite in the space segment and the mobile terminal on the ground is very long, so it is bound to have a strong correlation to place two or more antennas on a satellite [2].

It can be seen that only by establishing a satellite mobile communication channel model that can accurately and truly reflect the situation of masking and multipath that may be encountered in the actual signal transmission process, can we make a more in-depth study and analysis of the channel capacity and the factors affecting it. It is the premise of improving transmission efficiency and quality, and the basis of improving the performance of satellite mobile MIMO communication system. The research content of this paper also comes from this.

2 Measurement Activities and Characteristic Analysis of Satellite Mobile MIMO Channel

2.1 Representative Measurement Activities

The first and most representative measurement activity of satellite mobile MIMO channel characteristics was conducted by Peter R. king in Guildford, UK in the summer of 2005 [3]. He used antennas installed on an artificial platform at the top of a mountain to simulate the satellite antennas and installed them on a slope 6 meters above the ground to reduce local scattering. The main lobe of the antenna was far away from the terrain and was not blocked. The first side lobe of –20 dB was at the edge of the mountain covered by the grassland about 100 m away from the platform. The user terminal communicating with the antenna was simulated by a mobile van.

Three measurement environments were selected. The first environment is a tree-lined road with dense trees on both sides of the road, occasionally open space, and occasionally two-story houses outside the vegetation. The second environment is the suburb with dense two-story houses on both sides of the road and occasionally trees. The third environment is the city with dense two- to four-story houses and sporadic trees. The selection of these three environments is very representative, and the simulation environment assumptions and parameter selections later in this paper will also adopt these three environments, namely open rural, suburban, and urban environments.

Other representative measurement activities include the supplementary measurement activities conducted by Unwana M. Ekpe in Guildford, UK in 2009 and 2010 [4], and the ESA ARTES 5.1 MIMOSA [5], etc.

2.2 Characteristic Analysis of Satellite Mobile MIMO Channel

Based on the data collection, research and conclusion analysis of the above measurement activities, the channel characteristics which can be used for the subsequent modeling of MIMO channel are summarized as follows:

(1) In the statistical sense, the probability density function of the signal envelope is studied. The experimental data is subjected to the kolmogoroff-smirnoff test to

know that the large-scale fading conforms to the lognormal distribution, and the small-scale fading conforms to the Rice distribution.

(2) In terms of the correlation between sub-channels, only the signals with short time interval in the large-scale fading have a close correlation in the time domain, and the small-scale fading is weakly correlated.

(3) Satellite mobile MIMO channel has the correlation between channels, which is the biggest difference between it and terrestrial MIMO channel. It is also an important part that cannot be ignored in modeling.

3 Modeling of Satellite Mobile MIMO Channel

3.1 Modeling Scenario and Channel Matrix

The modeling environment of this paper selects open rural, suburban, and urban, and the channel is a 2 × 2 MIMO LMS channel. That is to say, a single GEO satellite as the sending end and a single ground mobile terminal as the receiving end both use the dual circular polarization antenna with left and right circular polarization elements. The selected operating frequency is the S-band. Since the multipath echo has no significant time-domain extension, the resulting fading channel is assumed to be narrow-band, that is, frequency non-selective.

Under the above conditions, the MIMO LMS channel is modeled by a 2 × 2 MIMO channel matrix $H = \left|h_{ij}\right|(i,j = 1,2)$. h_{ij} represents the fading component of SISO LMS subchannel formed between the transmitting side and the receiving side, where h_{11} and h_{22} represent the channel gain between antennas of the same polarization mode in the link, while h_{12} and h_{21} represent the channel gain between antennas of different polarization modes in the link. Since h_{ij} includes large-scale fading effect and small-scale fading effect, the channel matrix $\mathbf{H}$ can be expressed as the sum of two parts:

$$H = [h_{ij}] = [\overline{h}_{ij}] + [\widetilde{h}_{ij}] = [\overline{H}] + [\widetilde{H}](i,j = 1,2) \tag{1}$$

Where each land mobile satellite subchannel follows the C. loo distribution:

$$h_{ij} = \left|h_{ij}\right| \exp\left(j\phi_{ij}\right) = \left|\overline{h}_{ij}\right| \exp\left(j\overline{\phi}_{ij}\right) + \left|\widetilde{h}_{ij}\right| \exp\left(j\widetilde{\phi}_{ij}\right)(i,j = 1,2) \tag{2}$$

$$p(|h_i|) = \frac{|h_i|}{b_0\sqrt{2\pi d_0}} \int_0^{\infty} \frac{1}{z} \exp\left[-\frac{(\ln z - \mu)^2}{2d_0} - \frac{(|h_i|^2 + z^2)}{2b_0}\right] I_0\left(\frac{|h_i|z}{b_0}\right) dz \tag{3}$$

Where ϕ_0 and ϕ are uniformly distributed over [0, 2π). $\left|\overline{h}_i\right|$ represents the amplitude of large-scale fading, with *(α, ψ)* as the parameters, and it follows lognormal distribution. $\left|\widetilde{h}_i\right|$ represents the amplitude of small-scale fading, with *MP* as the parameter, and it follows Rayleigh distribution.

$\alpha = 20\log_{10}(e^{\mu})$ and $\psi = 20\log_{10}\left(e^{\sqrt{d_0}}\right)$ are the mean and standard deviation, and $MP = 10\log_{10}(2b_0)$ is the average power. *(α, ψ, MP)* is called C.Loo statistical parameter triplet, and $I_0(.)$ is the modified Bessel function of first kind and zero order.

3.2 Generation of Large-Scale Fading in Satellite Mobile Polarized MIMO Channel

In the MIMO LMS channel based on the C.Loo model, large-scale fading is mainly caused by the shadow effect, and its influence on the signal changes slowly, which is also known as slow fading. The detailed modeling process of large-scale fading is as follows:

(1) First, in each state, generate 2 × 2 samples of Gaussian random sequence with zero mean, unit variance, and independent distribution.

(2) These four independent sequences are respectively passed through the lowpass infinite impulse response filter, so the large-scale fading has temporal correlation to some extent. The lowpass filter to simulate temporal correlation can be expressed as:

$$y_n = x_n + By_{n-1} \tag{4}$$

Where $B = \exp(-vT/r_c)$, T is the sampling time, v is the speed of the ground mobile terminal, and r_c is the coherent distance. By multiplying by $(1 - B^2)$, the samples after low-pass filtering can keep the statistical characteristics before filtering, so that the 2 × 2 channel matrix $\overline{H}_{uncorr}$ can be generated.

(3) Because of the large distance between the satellite and the earth and the small space between the antennas at the receiving end, the large-scale fading part experiences serious spatial correlation. Therefore, a 2 × 2 Gaussian matrix with zero mean and unit variance is introduced to simulate the joint correlation. The correlated channel characteristic matrix $\overline{H}_{uncorr}$ is represented by covariance matrix $\overline{H}_{corr}$ and uncorrelated channel characteristic matrix $\overline{C}$ as follows:

$$vec(\overline{H}_{corr}) = \overline{C}^{\frac{1}{2}} vec(\overline{H}_{uncorr}) \tag{5}$$

(4) In order to generate a lognormal channel matrix, the Gaussian matrix $\overline{H}_{corr}$ needs to be combined with the mean α and the standard deviation ψ, resulting in a large-scale fading channel matrix $\overline{H}$:

$$vec(\overline{H}) = 10^{\left[vec(\overline{H}_{corr})(\psi/20) + (\alpha/20)\right]} \tag{6}$$

(5) In addition to the change in signal amplitude, the Doppler shift will cause the linear change in the phase of the direct signal:

$$f = (v/\lambda)\cos\varphi\cos\theta \tag{7}$$

Where φ and θ are the azimuth and elevation angles of the user terminal, v is the moving speed of the user terminal, and λ is the signal wavelength. The constant phase increment is as follows:

$$\Delta\phi = 2\pi\frac{\cos\varphi\cos\theta}{F} \tag{8}$$

Where F is the reciprocal of the wavelength, and λ/F is the signal sampling interval.

(6) The influence of polarization diversity is described by the parameter cross polarization discrimination XPD_{ant}, which represents the ability of antennas to distinguish orthogonal polarization components. XPD_{ant} can be expressed as:

$$XPD_{ant} = 10\log_{10}\left(\frac{E\left[\left|\bar{h}_{ij}^{j}\right|\right]}{E\left[\left|\bar{h}_{ij}^{k}\right|\right]}\right) = 10log_{10}\left[\frac{(1-\beta)}{\beta}\right] \tag{9}$$

Because the actual value of the XPD of the satellite antenna (i.e., the transmission side) is very large, it is assumed to be approximately ∞. XPD_{ant} here only represents the XPD of the receiving antenna that seriously affects the analysis. Generally, XPD_{ant} is known, so β can be inversely deduced with the above formula. Therefore, the influence of polarization on channel power can be expressed as follows:

$$\begin{bmatrix} E\left\{\left|\bar{h}_{11}^{k}\right|^2\right\} & E\left\{\left|\bar{h}_{12}^{k}\right|^2\right\} \\ E\left\{\left|\bar{h}_{21}^{k}\right|^2\right\} & E\left\{\left|\bar{h}_{22}^{k}\right|^2\right\} \end{bmatrix} = MP\begin{bmatrix} 1-\beta & \beta \\ \beta & 1-\beta \end{bmatrix} \tag{10}$$

3.3 Generation of Small-Scale Fading in Satellite Mobile Polarized MIMO Channel

In the process of radio wave propagation, in addition to large-scale fading caused by shadow effect, multipath effect and Doppler spread will also cause small-scale fading. Small-scale fading reflects the rapid fluctuation characteristics of received signals within a short distance and time, which is also known as fast fading. Due to the angular spread $\delta\theta$ caused by multipath and the multi-antenna cooperative localization of the user terminal, as well as the distance Δ between the antennas in the antenna array, the small-scale fading component $\tilde{h}_i$ is affected by the space-time correlation at the receiving end. The detailed modeling process is as follows:

(1) First, in each state, generate 2 × 2 samples of complex Gaussian random sequence with zero mean, unit variance, and independent distribution.
(2) Then, the samples are respectively passed through a lowpass U-shaped filter with unit energy, and the Butterworth filter will cause Doppler expansion. After Doppler shaping, the resulting complex sequence is multiplied by $\sqrt{b_0}$ to form a Rayleigh sequence. The elements in the sequence are arranged to form a matrix $\tilde{H}$ which is a 2 × 2 channel matrix with independent identically distributed zero mean circularly symmetric complex Gaussian elements of variance *MP*.
(3) Then, the correlation between the MIMO subchannels is generated to obtain a 2 × 2 MIMO small-scale fading channel matrix $\tilde{H}$. The formula used here is:

$$\tilde{H} = \tilde{R}_{rx}^{1/2} \cdot \tilde{H}_w \cdot \tilde{R}_{tx}^{1/2} \tag{11}$$

Where $\tilde{R}_{rx}$ and $\tilde{R}_{tx}$ are the covariance matrixes.
(4) Because the cross polarization discrimination of small-scale fading component $\tilde{h}_{ij}(i,j = 1,2)$ is related to *XPC* of the propagation environment (expressed by XPC_{env}) and XPD_{ant}, the influence of polarization on channel power in small-scale fading can be expressed as follows:

$$\begin{bmatrix} E\left\{\left|\tilde{h}_{11}^k\right|^2\right\} & E\left\{\left|\tilde{h}_{12}^k\right|^2\right\} \\ E\left\{\left|\tilde{h}_{21}^k\right|^2\right\} & E\left\{\left|\tilde{h}_{22}^k\right|^2\right\} \end{bmatrix} = MP\begin{bmatrix} 1-\gamma & \gamma \\ \gamma & 1-\gamma \end{bmatrix} \tag{12}$$

Where the parameter γ is jointly determined by $XPC_{env} = 10\log_{10}[(1-\gamma_{env})/\gamma_{env}]$ and $\gamma = \beta(1-\gamma_{env}) + (1-\beta)\gamma_{env}$. β is the same as that of the large-scale fading part. *MP* represents the average power.

Using formula (1) to combine the large-scale fading part with the small-scale fading part, the final channel matrix **H** can be obtained. The complete satellite mobile MIMO channel modeling process is shown in Fig. 1.

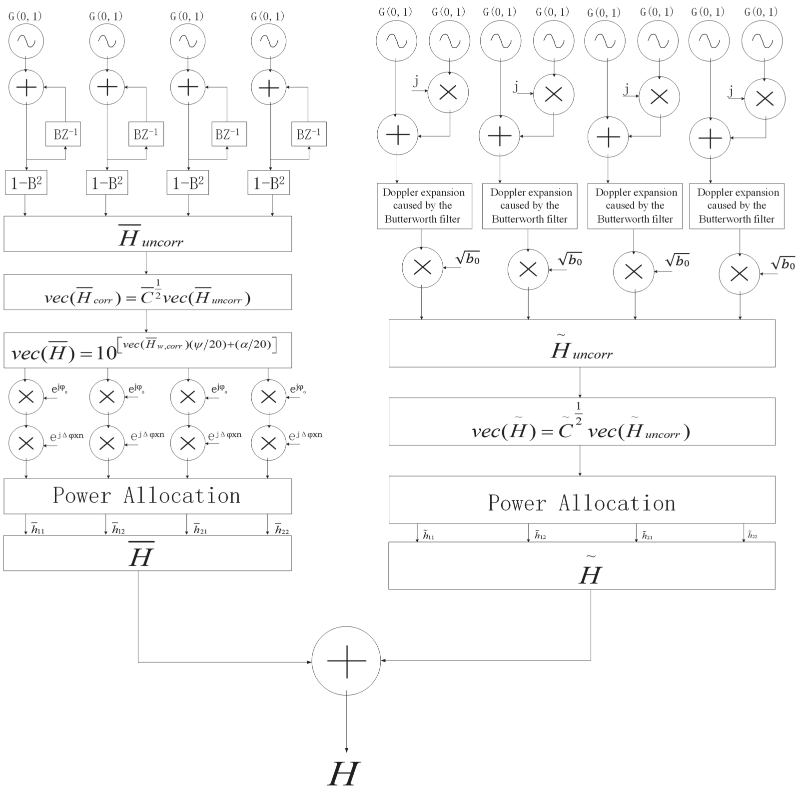

Fig. 1. Modeling process of satellite mobile MIMO channel

4 Simulation Analysis of Satellite Mobile MIMO Channel Model

Based on the established model, this chapter carries on the simulation analysis to the satellite mobile MIMO channel model.

In order to study the effect of different simulation parameters on the 1% outage capacity representing system performance, Fig. 2, Fig. 3 and Fig. 4 respectively simulate the influence of environment, antenna cross polarization discrimination and satellite elevation on system performance. It can be found that the performance of MIMO system is significantly better than that of SISO system, which is about double the improvement. Simulation environments will significantly affect the performance of the MIMO system, and open rural is the best while urban is the worst. What's more, larger cross polarization discrimination and satellite elevation can improve the system performance.

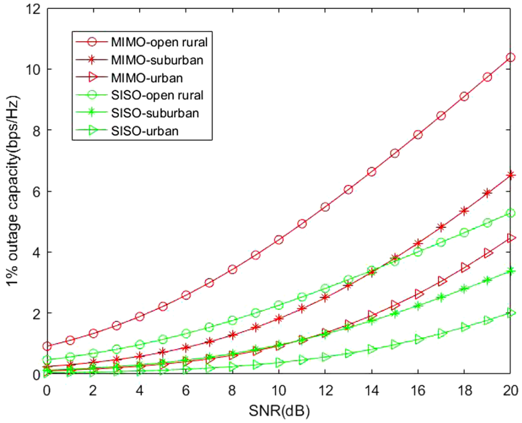

Fig. 2. 1% outage capacity of MIMO and SISO channel in different simulation environments

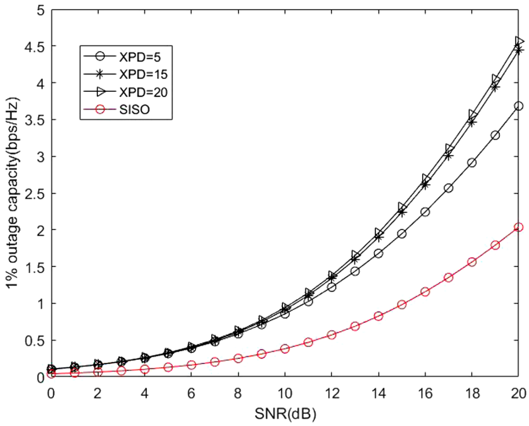

Fig. 3. 1% outage capacity of different cross polarization discriminations in urban environment

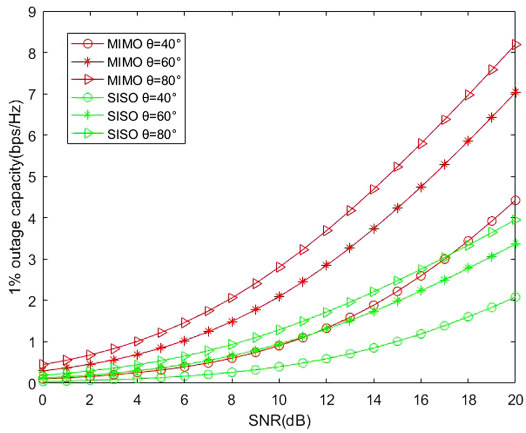

Fig. 4. 1% outage capacity of different satellite elevations in urban simulation environment

5 Conclusion

This paper summarizes the characteristics of the MIMO channel through the analysis of measurement activities and gives a modeling method of the narrow-band satellite mobile dual polarization 2 × 2 MIMO channel model based on two-state Markov chain. On this basis, the sub-channels' time series and the influence of different parameters on system performance is simulated. It is concluded that the performance of MIMO system is significantly better than that of SISO system; different simulation environments will significantly affect the performance of the MIMO system, and open rural is the best while urban is the worst; larger cross polarization discrimination and satellite elevation can improve the system performance. All of them provide theoretical support for the application of MIMO technology in satellite mobile communication system.

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