Channel Modeling and Characteristics for High Altitude Platform Stations Communication System

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Abstract

The research on high altitude platform stations (HAPS) system and HAPS mobile high-speed communication system is still in its infancy. In the absence of valid description of HAPS mobile channel characteristics, there are few special research on signal transmission and data processing technologies in HAPS mobile communications. When analyzing the angular spectrum of multipath scattering distribution in HAPS mobile channel, the plane wave assumption of ground wireless mobile channel is no longer valid, and it is necessary to consider the extension of the elevation and azimuth at the mobile terminal. The HAPS mobile channel characteristic system is constructed by software simulation, which provides channel models and parameters in different environments for the broadband HAPS mobile communication system and its ground simulation and verification system.

Keywords: HAPS, Communication, Channel characteristics, Channel modeling

1 Introduction

The developing high altitude platform stations (HAPS) [1-3], the height of which is between the ground and various communication satellites. Owing to excellent radio wave transmission characteristics, the communication connection between users on the ground, platforms or platforms and satellites can be finished through the platform, which has the advantages of flexible layout, wide application, low cost, safety and reliability. The communication platform keeps synchronization with the rotation of the earth and can stay in the air for a long time. On account of its characteristics of low cost, rapid deployment, less ground equipment, flexible use and convenient recovery and exchange channels can be quickly established over the battlefield, and field inbeam-forming can be quickly and accurately transmitted to the command center, so as to achieve the purpose of real-time command operations. Moreover, the system can also provide continuously monitor the ground and sky in 1000 km and nearly one million kilometers area. Within the coverage of high altitude platform, cellular network structure can still be used to organize communication [4-6].

As a national fundamental communication establishment and part of global mobile communication, HAPS mobile communication has a wide range of applications in national security, emergency rescue, internet, remote education, satellite television broadcasting and personal mobile communications. In the new generation of mobile communication systems, the system must have higher transmission rate and higher spectrum efficiency to meet the transmission requirements of broadband multimedia services. During the research of broadband HAPS mobile communication system and its ground simulation verification system, a necessary work is to study the characteristics of channel propagation [7-10]. In order to achieve reliable transmission of inbeam-forming, various communication technologies must be selected for the channel propagation characteristics in the stage of planning or design. At the same time, the channel model can be easily simulated to verify the practicability and efficiency of various communication technologies [11-12].

In general, the research on the fading characteristics of HAPS mobile channel is more focused on the time domain dispersion characteristics and frequency domain dispersion characteristics of the channel. According to the different environments of the mobile terminals, the HAPS mobile channel models can be divided into two categories: single-state model and multi-state model [13-16]. The single-state model assumes that the envelope or power of the received signal follows a uniquely determined probability distribution and is suitable for describing stationary channels. When the mobile terminal moves in a wide range, the multi-state model can be used to describe the channel characteristics because it exceeds the range described by the single-state model. Due to its multiple states, the multi-state model is suitable for describing non-stationary channels, and different states correspond

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to different types of probability density distributions or the same types of probability distributions with different parameters [17-18]. With the development of social economy, civil and military HAPS mobile communication is more and more widely used, and the demand for high-speed and high-quality data transmission is more urgent, which puts forward higher requirements for the transmission bandwidth of HAPS mobile communication system. In the reality of increasingly scarce frequency resources, using advanced communication technology to improve spectrum utilization and increase system capacity has become the inevitable direction for the development of HAPS mobile communication [19-20]. By using space-time coding, the advantages of space diversity and time diversity can be synthesized, and diversity gain and coding gain can be provided, which greatly improves the spectrum utilization. Due to the inherent characteristics of HAPS mobile communication, channel modeling needs to take full account of various factors, such as the large delay difference (which generates inter-symbol interference), large Doppler frequency shift in different paths (which causes channel dispersion effect in frequency domain and determines whether the signal undergoes slow or fast fading), the multipath effects caused by the environment around mobile terminals, the time-domain dispersion effects caused by shadow effects (which determines whether the channel is broadband or not), the stability of signal path (which decides whether single-state model or multi-state model) and the spatial correlation between signals of different paths.

The channel characteristics include multistate model of broadband HAPS mobile channel and impulse response model of broadband HAPS mobile channel were established in section 2. The channel simulation of broadband HAPS communication system was finished in section 3 and some conclusions were discussed in section 4.

2 Channel Characteristics

2.1 Multistate Model of Broadband HAPS Mobile Channel

Since the multi-state HAPS mobile channel model in wide-area environment needs to dynamically switch back and forth between multiple states randomly, a handover method that can simulate the actual situation better is needed. Generally, the state of random signal at a certain moment is mainly affected by the state of the signal at the last time, while the state of the signal away from the moment has little or no influence. Thus, a mathematical Markov chain model is used to realize the stochastic switching process.

Let the parameter set T of stochastic process $\{X_n, n\in T\}$ be a discrete time set, that is to say, $T=\{0,1,2,...\}$, the state space consisting of all possible values of its corresponding X_n is the discrete state set $S=\{0,1,2,...\}$. If the conditional probability satisfies

$$P\{X_{n+1}=i_{n+1} \mid X_0=i_0, X_1=i_1,...,X_n=i_n\} = P\{X_{n+1}=i_{n+1} \mid X_n=i_n\}$$

for any integer $n\in T$ and $i_0,i_1,...,i_{n+1}\in S$, then $\{X_n, n\in T\}$ is called Markov chain. There are two important matrices in Markov chains. One is the state probability matrix W, which represents the set of probabilities that may occur in each state under certain circumstances. The other is the state transition matrix P, which is composed of state transition probability. The intuitive meaning of the conditional probability $p\{X_{n+1}=j \mid X_n=i\}$ is the probability that the system is in state j at time $n+1$ under the condition that the system is in state i at time n, which is recorded as $p_{ij}(n)$. This conditional probability is the one-step transition probability of Markov chain $\{X_n, n\in T\}$ at time n, referred to as transition probability.

When HAPS mobile channel is described by Markov chain, finite states are used to quantize the channel parameters instead of infinite states. Therefore, Markov model is also called Finite State Markov Channel (FSMC). With the FSMC model describing, the signal amplitude $r(t)$ is first normalized to eliminate path loss for the direct component and sampled, and then quantified into K (K≥2) states r_n, These discrete states can be considered as the state of the Markov chain. Assuming that the quantization threshold is $\{R_k\}$, where k=1,2,…K, R_1=0 dB and R_K=-∞. At each sampling point, the channel state is S_n=S_k when $r_n\in[R_k, R_{k+1})$. Consequently, the channel can be represented as a Markov chain $\{S_n\}$ of K state, and its state probability $p_i(n)$ and the transition probability $p_{ij}(n, s)$ of n-s step are respectively:

$$\begin{cases} p_i(n)=\Pr(S_n=i) \\ p_{ij}(n,s)=\Pr(S_s=j/S_n=i) \end{cases} \quad i,j\in\{0,1,...K-1\} \tag{1}$$

When establishing the FSMC model for HAPS mobile channel, the following assumptions are generally made: (1) The signal come through the slow fading channel, namely, the amplitude of the received signal remains unchanged within a sampling period of T; (2) The established Markov chain $\{S_n\}$ is a stationary chain, that is, the probability value $p_{ij}(n, s)$=$p_{ij}(n\text{-}s)$ of state transition in Markov chain is only related to the time difference n-s, and the probability distribution $p_i(n)$= p_i of all States is independent of the sampling time nT; (3) The amplitude of the signal between adjacent sampling points is continuous, that is, when the condition $\forall |i-j|>1$ and $|n-s|=1$ are satisfied, the state transition probability of the channel satisfies equation $p_{ij}(n, s)$=0. Based on the above assumptions, for the FSMC model, the state probability matrix W and one-step transition probability matrix P of its Markov chain can be used to describe the state change of HAPS mobile channel.

In the FSMC model, the probability that the quantized channel is in the state k is:

$$p_k = p(s_k) = \Pr(R_k \le r \le R_{k+1}) = \int_{R_k}^{R_{k+1}} f(r)dr \quad \textbf{(2)}$$

There are two methods to determine the one-step transition probability matrix. One is based on the conditional probability of each state interval, which is the most direct method to obtain the transition probability matrix of the Markov chain from the basic definition of the transition probability. The other way to determine one-step transition probability matrix is based on the level crossing rate of HAPS mobile channel, where the transition probability between different states can be expressed as:

$$\begin{cases} p_{k,k+1} = N_{k+1}T/p_k & k = 1,2...,K-1 \\ p_{k,k-1} = N_k T/p_k & k = 2,3,...,K \\ p_{k,k} = 1 - p_{k,k-1} - p_{k,k+1} & k = 2,3...,K-1 \end{cases} \quad \textbf{(3)}$$

Where N_{k+1} is the level crossing rate at R_{k+1}; N_k is the level crossing rate at R_k; p_k is the probability of the k th state.

2.2 Impulse Response Model of Broadband HAPS Mobile Channel

One of the most commonly used probabilistic statistical models for describing frequency-selective fading channels is the generalized stationary uncorrelated scattering model. The so-called generalized stationary means that the impulse response of the channel is generalized stationary, and there is no correlation between multipaths with different Doppler frequencies. The so-called uncorrelated scattering means that the multipath with different propagation delays is uncorrelated. The impulse response function contains inbeam-forming for analyzing the propagation characteristics of wireless channels, which can be used to compare the performance of different mobile communication systems and to characterize the fading characteristics of broadband channels. Generally, the propagation characteristics of broadband HAPS mobile multipath channel are modeled as a linear filter with time-varying impulse response function, whose filtering characteristics are determined by the magnitude and delay of multipath.

$h(t,\tau)$ is defined as the response of time-varying frequency-selective HAPS mobile channel at time t-τ when impulse is applied at time t:

$$h(t,\tau) = \sum_{l=1}^{N} a_l(t,\tau)\exp\left[j\theta_l(t,\tau)\right]\delta\left(\tau - \tau_l(t)\right) \quad \textbf{(4)}$$

Where l is the channel index, N is the number of multipath components, and $\{a_l(t,\tau)\}_{l=1}^{N}$, $\{\theta_l(t,\tau)\}_{l=1}^{N}$, and $\{\tau_l(t)\}_{l=1}^{N}$ are the amplitude, phase, and delay components of the random channel, respectively (the first path is usually the direct path and the reference path, τ_1=0).

In the given impulse response condition, if the multipath is generated by different scattering sources. These paths can be considered to be independent of each other, thus $\{a_l(t,\tau)\}_{l=1}^{N}$ is a statistically independent stochastic process. For random time-varying wireless mobile channels, it is hard to require the multidimensional probability density function of channel impulse response. In practical applications, the impulse response autocorrelation function or one of its Fourier transforms is usually used to characterize the broadband frequency selective HAPS mobile channel. Based on impulse response, a series of characteristic functions, such as the scattering function, the frequency interval-time interval correlation function, the power delay spectrum and the Doppler power spectrum, can be obtained for frequency-selective HAPS mobile channel. Under the assumption of generalized stationary uncorrelated scattering, the autocorrelation function $\varphi_h(t_1;t_2;\tau_1;\tau_2)$ of response $h(t,\tau)$ is:

$$\begin{aligned} \phi_h(t_1,t_2;\tau_1,\tau_2) &= \frac{1}{2}E\left[h^*(t_1;\tau_1)h(t_2;\tau_2)\right] \\ &= \phi_h(\Delta t;\tau_1,\tau_2) = \phi_h(\Delta t;\tau_1)\delta(\tau_1 - \tau_2) \end{aligned} \quad \textbf{(5)}$$

When $\Delta t = 0$, $\varphi_h(\tau)$= $\varphi_h(\tau,0)$ is the power delay spectrum of the channel, which describes the relationship between the average received power of the channel and the multipath delay τ:

$$\phi_h(\tau) = \phi_h(\tau;0) = \frac{1}{2}E\left[h^*(\tau;t)h(\tau;t)\right] \quad \textbf{(6)}$$

The time-varying transfer function $H(f,t)$ of the channel can be obtained by Fourier transform of $h(\tau,t)$ to τ:

$$H(f,t) = \int_0^{\infty} h(\tau,t)e^{-j2\pi f\tau}d\tau \quad \textbf{(7)}$$

If $h(\tau,t)$ is a generalized stationary uncorrelated scattering Gaussian random process, then $H(f,t)$ is also a WSSUS (Wide-Sense Stationary Uncorrelated Scattering) Gaussian random process, so its autocorrelation function for f and t is:

$$\phi_H(\Delta f,\Delta t) = \frac{1}{2}E\left[H^*(f;t)H(f+\Delta f;t+\Delta t)\right] \quad \textbf{(8)}$$

The equation (9) is worked out by substituting equations (5) and (7) into equation (8),

$$\phi_H(\Delta f,\Delta t) = \int_{-\infty}^{+\infty}\phi_h(\tau;\Delta t)e^{-j2\pi\Delta f\tau}d\tau \quad \textbf{(9)}$$

When $\Delta t = 0$, the frequency interval correlation function $\phi_H(\Delta f)$ of the channel can be obtained as follows

$$\phi_H(\Delta f) = \phi_H(\Delta f;0) = \int_{-\infty}^{+\infty} \phi_h(\tau) e^{-j2\pi\Delta f \tau} d\tau \quad \textbf{(10)}$$

Equation (10) illustrates that the frequency interval correlation function $\phi_H(\Delta f)$ is the Fourier transform of the power delay spectrum $\varphi_h(\tau)$, which describes the correlation of the channels with the frequency interval Δf. $\varphi_h(\tau)$ and $\phi_H(\Delta f)$ reflect the frequency fading characteristics of the channel.

Another useful channel characteristic function is derived from $\phi_H(\Delta f, \Delta t)$: Doppler power spectrum. In this case, the Fourier transform of $\phi_H(\Delta f, \Delta t)$ to variable Δt is defined by using the time interval correlation function $\phi_H(\Delta t)$ of the channel:

$$S(\Delta f, f_d) = \int_{-\infty}^{+\infty} \phi_H(\Delta f;\Delta t) e^{-j2\pi f_d \Delta t} d\Delta t \quad \textbf{(11)}$$

When $\Delta f = 0$, the Doppler power spectrum $S(f_d)$ of the channel can be obtained by the above equation (11):

$$S(f_d) = \int_{-\infty}^{+\infty} \phi_H(\Delta t) e^{-j2\pi f_d \Delta t} d\Delta t \quad \textbf{(12)}$$

The relationship between signal strength and Doppler frequency is given. Equation (12) shows that the time interval correlation function $\phi_H(\Delta t)$ is the inverse Fourier transform of the Doppler power spectrum $S(f_d)$, and represents the correlation of the channels with the time interval Δt. $S(f_d)$ and $\phi_H(\Delta t)$ represent the time-varying characteristics of the channel.

The scattering function $S(\tau, f_d)$ of channel can be obtained by two-dimensional Fourier transform of $\phi_H(\Delta f, \Delta t)$ with respect to Δf and Δt:

$$S(\tau, f_d) = \iint \phi_H(\Delta f;\Delta t) e^{-j2\pi\tau\Delta f} e^{-j2\pi f_d \Delta t} d\Delta f d\Delta t \quad \textbf{(13)}$$

The scattering function, also known as delay-Doppler power spectrum, is a two-dimensional function. As a function of time-domain variable (delay τ) and frequency-domain variable (Doppler frequency f_d), it expressly represents the time-domain and frequency-domain dispersion properties of the channel. The scattering function can also be used to describe two kinds of extensions in multipath dispersive mobile channels, namely, the delay spread induced by multipath effect in time domain and Doppler spread induced by Doppler effect in frequency domain. The power delay spectrum $\phi_h(\tau)$ and Doppler power spectrum $S(f_d)$ of the channel can be obtained by calculating the marginal function of the scattering function on Doppler frequency f_d and time delay Δt, respectively, as shown in Figure 2.

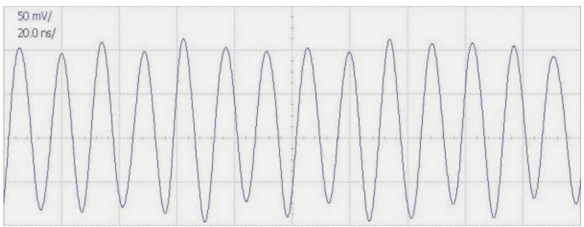
$$\phi_h(\tau) = \int_{-\infty}^{+\infty} S(\tau, f_d) df_d \quad \textbf{(14)}$$

$$S(f_d) = \int_{-\infty}^{+\infty} S(\tau, f_d) d\tau \quad \textbf{(15)}$$

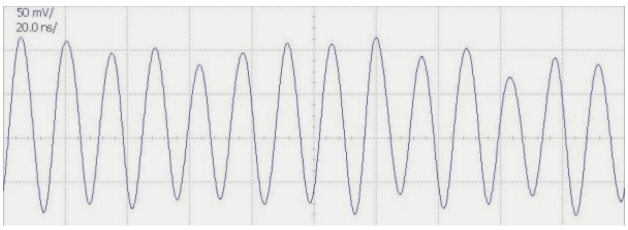
3 Channel Simulation of Broadband HAPS Communication System

In this paper, the L/S band broadband HAPS mobile channel simulator is simulated by software simulation, which is used to simulate the real-time channel characteristics of user links between platforms and mobile terminals in various scenarios in the ground simulation of HAPS mobile communication system. In the research, the parameters of the model in three typical real channel environments (light shadows in open areas, moderate shadows in rural areas and heavy shadows in urban areas) are fitted by the least mean square error criterion and linear least squares method based on the measured data of channel characteristics in high-grade highway (110 km/h) open environment, sparse trees on both sides of the rural highway, tree height of about 3-5m environment and urban area (25 km/h) environment.

Figure 1 exhibits the output waveform before and after superimposing channel characteristics in open terrain environment (light shadows). Figure 2 shows the comparison of the statistical characteristics of the signal amplitude with the theoretical model after the input signals of the channel simulator are superimposed on the channel characteristics of the open terrain environment.



(a) Signal waveforms before superimposing channel characteristics



(b) Signal waveforms after superimposing channel characteristics

Figure 1. Output waveforms before and after superimposing channel characteristics in open terrain environment

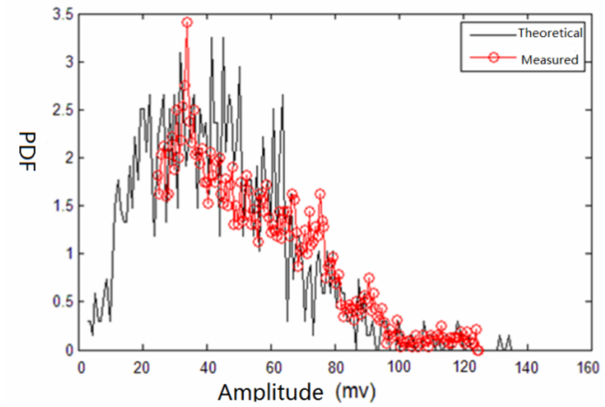
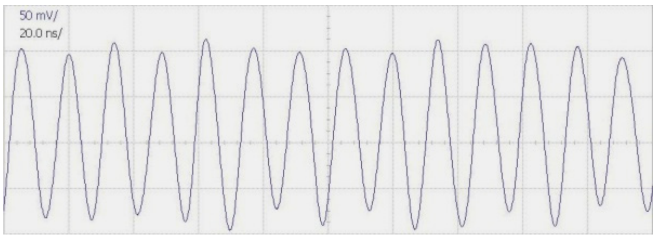
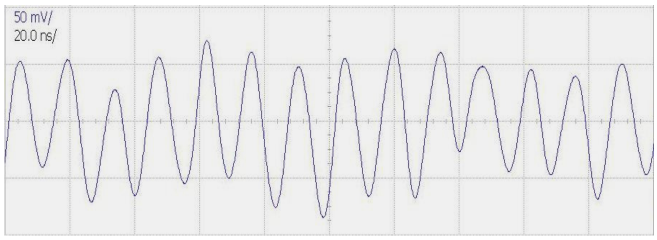


Figure 2. Probability density function (PDF) of signal amplitude after superimposing channel characteristics in open terrain environment

Figure 3 shows the output signal waveform before and after the channel analog input signal is superimposed on the channel characteristics of suburban environment (medium shadows). Figure 4 demonstrates a comparison between the statistical characteristics of the output signal amplitude and the theoretical model after the channel analog input signal is superimposed on the channel characteristics of suburban environment.



(a) Signal waveform before superimposing channel characteristics



(b) Signal waveform after superimposing channel characteristics

Figure 3. Output waveforms before and after superimposing suburban environmental channel characteristics

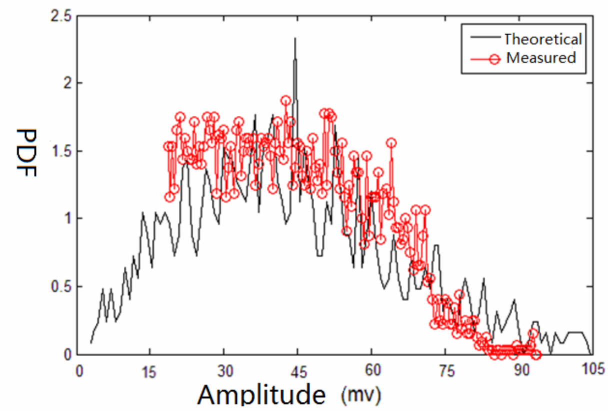
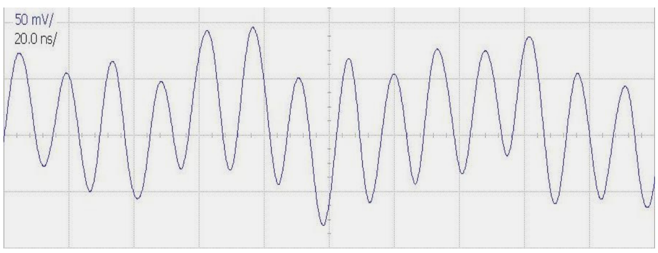


Figure 4. PDF of output signal amplitude after superimposing the characteristics of suburban environment channel

Figure 5 shows the output signal waveform before and after the channel analog input signal is superimposed on the environment channel characteristics of urban area (heavy shadows). Figure 6 is a comparison between the statistical characteristics of the output signal amplitude and the theoretical model after the channel analog input signal is superimposed on the urban environment channel characteristics.

(a) Signal waveform before superimposing channel characteristics



(b) Signal waveform after superimposing channel characteristics

Figure 5. Output signal waveforms before and after superimposing urban environmental channel characteristics

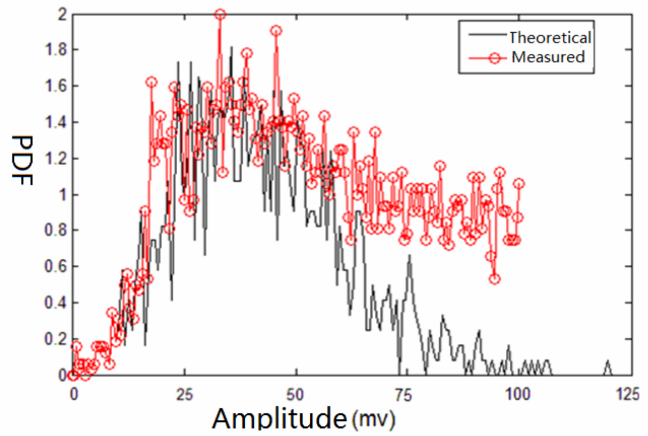


Figure 6. PDF of the output signal amplitude after superimposing the characteristics of urban environmental channel

Figure 1, Figure 3 and Figure 5 show the received signal sequence in urban environment, rural environment and suburban environment respectively. It can be seen that with the change of the channel environment, the propagation delay of the signal is also different, so the fading degree of the received signal is also different. For the rural environment, the signal fading is relatively flat, and large fading may occur, but when large fading occurs, they almost happen in the whole signal bandwidth. In suburban environment, due to the shelter of buildings, the signal delay is also increased, so the fading degree of the received signal is also increased. For the bad urban environment, we can see that the received signal has a serious fading. This is because in the bad urban environment, the signal delay is relatively large, so there is a serious crosstalk between symbols, and the received signal also shows a relatively large degree of fading.

Figure 2, Figure 4 and Figure 6 are probability density function (PDF) distributions of statistical characteristics of measured signals and theoretical signals in urban, rural and suburban environments respectively. The black line is the statistical characteristic curve of the theoretical model and the red line is the measured data. It can be seen from the figure that the statistical characteristics of the theoretical simulation model are very close to the measured data. And with the increase of the amplitude in each graph, the depth of fading is also deepened.

4 Conclusion

In this paper, when analyzing the angular spectrum of multipath scattering distribution in the HAPS mobile channel, it is necessary to consider both elevation and azimuth spread at mobile terminals since the plane wave assumption of terrestrial wireless mobile channel is not valid. In addition, due to the large delay difference, the large Doppler frequency shift and the strong spatial correlation between different paths in the HAPS mobile channel, the difficulty of channel characteristic analysis will increase. In this paper, by analyzing the time domain dispersion characteristics, frequency domain dispersion characteristics and the joint dispersion characteristics in space, time and frequency domains of wideband HAPS mobile channels, a broadband HAPS mobile channel model based on tapped delay line in a wide area environment is established. Finally, the HAPS mobile channel characteristic system is constructed by software simulation, which provides channel models and parameters in different environments for the broadband HAPS mobile communication system and its ground simulation and verification system.

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