Analysis and Modeling of UAV Near-ground Communication Channel

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Abstract. UAV communication platform has become a reliable solution to meet the needs of users in some unexpected situations. In this paper, the statistical method of small area modeling is used to model the UAV near-ground communication channel. The channel is abstracted into three factors: time-delay power spectrum, Doppler power spectrum and Rice factor. As a result, a new method of channel delay generation is introduced, and the time-varying Doppler frequency gain factor is adopted. The simulation results show that the UAV near-ground communication channel is a Rice channel whose amplitude obeys Rayleigh distribution and phase obeys uniform distribution. The bit-error-rate of UAV near-ground communication channel is much higher than that of AWGN channel. At the same time, the constellation chart also shows that the signal passing through the UAV near-ground communication channel will cause strong inter-symbol crosstalk.

1. Introduction

Recently, for earthquake, large-area network and other emergency scenarios, the use of UAV to build data relay platform has become a new focus of research\(^[1]\). The quality of the data relay platform largely depends on the reliability of communication between UAVs. UAV generally flies at a low altitude of 100m to 1000m, and there are many reflections and scatters from the ground, trees and buildings. Therefore, the signal received by UAV is often not a single direct path, but multi-path\(^[2]\). The relative motion of the UAV and the receiving antenna causes different Doppler spread and time delay in each path, and the multi-path signal has different phases at the receiver, which leads to the attenuation of the superimposed signal and serious inter-symbol crosstalk. It leads to high bit error rate and affects the performance of the platform. In order to solve these problems, the establishment of channel model is the basis of our work.

Wireless channel modeling is usually based on WSSUS criterion\(^[3]\). \(^[4]\) is based on aviation channel, extracting channel characteristics, and modeling by Doppler power spectrum, delay power spectrum and Rice factor, but the specific implementation method is not given. In \(^[5]\), the Doppler spectrum is modeled by SoS method for aviation channel, and the specific implementation method is given, but the modeling is not accurate because the frequency gain assumption is time-invariant. The measurement in \(^[6]\) points out that WSSUS is established only in a short time slot, and the actual signal transmission will experience time-varying multi-path channels. Based on the idea of piece-wise stationary fading channel simulation, the author establishes a time-varying Doppler power spectrum model in \(^[7]\). In \(^[8]\), A new random broadband dynamic channel simulation model is proposed, but its implementation structure is more complex and is not easy to be implemented in hardware.In \(^[9]\), the
frequency gain is adjusted to time-varying, but the channel model is a real channel, and the delay power spectrum is not taken into account. Based on this, the channel is modeled as time-varying, and the delay power spectrum is modeled, and a discrete and complete aviation channel model is obtained.

The outline of this paper is as follows. In Section 2 the difference between small-area model and large-area model is explained, and the main factors to be considered in multi-path channel modeling are discussed. In Section 3, the modeling method of delay power spectrum is mentioned, and the acquisition methods of each delay are also given in detail. In Section 4, the time-varying Doppler power spectrum model is established. Simulation results for the UAV near-ground communication channel are presented for a QPSK system in Section 5. Conclusions are drawn in Section 6.

2. Small-area model

Wireless channel modeling can be divided into two types: large-area model and small-area model. The large-area model mainly describes the situation of signal attenuation and being blocked by obstacles in the process of long-distance transmission, the typical application is the modeling of radar wave transmission channel. The small-area model mainly describes the rapid change of signal strength in a short distance and a short time. In addition to the multi-path propagation, the model also takes into account the shadow and propagation path loss, and the reflection coefficient of different media. This model can be used for link design and can also be used as the basis of the service model. However, they are usually not necessary for the design or verification of physical layer transmission technology. In the low-altitude communication channel modeling of UAV, we mainly consider the design or verification of physical layer transmission technology, that is, small-area model in Figure 1.

According to the WSSUS (Wide-sense Stationary Uncorrelated Scattering), three parameters can be used to describe the low-altitude flight channel of UAV, namely, Rice factor, delay power spectrum and Doppler power spectrum. Rice factor characterizes the type of decline [4]. When the signal transmission goes through multiple scattering paths, according to the central limit theorem, the compound paths composed of these paths obey Rayleigh distribution, while the direct paths obey normal distribution. The combination of the LOS path and the scattering path makes the amplitude of the signal received by the UAV antenna show a Rice distribution, and the magnitude of the Rice factor is equal to the power ratio between the LOS path and the scattering path.

\[ K_R = \frac{a^2}{c^2} \quad \text{or equivalently} \quad K_R = 10 \log_{10} \frac{a^2}{c^2} \text{dB} \] (1)

Where \( a \) is the signal amplitude of the LOS path and \( c^2 \) is the variance of the scattering channel. And it is assumed that the power of the channel is constant, \( a^2 + c^2 = 1 \). In particular, when \( K_R = 0 \), there is only the scattering path, the received signal is Rayleigh distribution. When the amount of scattering is very small, \( K_R \rightarrow \infty \), which is equivalent to only the LOS path, the channel is a AWGN (Additive White Gaussian Noise) channel. The other value is the Rice distribution when
both the LOS path and the scattering path exist with large signal strength. In the process of near-
ground flight, the scattering path signal received by the receiver has a certain delay compared with the
LOS path signal, and when the maximum delay time is greater than the transmission time of the signal
pulse, it will cause serious inter-symbol crosstalk and affect the final signal decision. The delay power
spectrum reflects the average power of different delay multi-path components. At the same time, the
unit impulse response of the multi-path channel varies with time, and the reason for the change is that
the intensity of the scattered signal changes due to the relative motion between the UAV and the
multi-path, and the incident angle and the direction of the relative motion of the signal are different in
the multi-path. As a result, the magnitude and positive or negative of the Doppler shift generated by
each channel are also different, so it is only necessary to determine the maximum Doppler shift when
studying the dynamic characteristics of the channel. The channel parameters of UAV flying at low
altitude near the ground are similar to those in rural areas. We use COST-207 as a reference and
verification [10].

\[ P(\tau) = \begin{cases} 
    e^{-\tau / \tau_{\text{slope}}} & 0 \leq \tau \leq \tau_{\text{max}} \\
    0 & \text{else.}
\end{cases} \]  

(2)

In the equation, \( \tau_{\text{max}} \) represents the maximum delay and \( \tau_{\text{slope}} \) represents the attenuation rate.

In [4], a method for generating random multi-path delay is proposed:

\[ \tau_k(l) = -\tau_{\text{slope}} \cdot \ln(1 - e^{-\tau_{\text{max}} / \tau_{\text{slope}}}) \]

\[ \approx -\tau_{\text{slope}} \cdot \ln(1 - \mu_s) \]  

(3)

In the formula, \( \mu_s \) is a random vector, which obeys (0,1) uniform distribution.

However, after the simulation, we find that the fitting effect of the delay power spectrum of multi-
path delay is not ideal, so the follow formula is adopted. Figure 3 shows that the new method fits delay
power spectrum well.

\[ \tau_k(l) = \mu_s \cdot \tau_{\text{max}} \]  

(4)

Figure 2. Doppler power spectrum and delay power spectrum of near-ground communication of
UAV

3. Delay power spectrum

It is pointed out in [4] that the typical power spectrum of multi-path delay in aviation channel is single
sideband exponential attenuation. As shown in Figure 2.
Figure 3. Fitting of delay power spectrum

4. Analysis of time-varying SoS Model
The SoS model proposed by Clarke and its improved model are simple and easy to implement[11]. It has been widely used. The normalized complex Gaussian stochastic process generated by reference can be expressed as follows:

\[ h_l(t) = h_{l,j}(t) + jh_{l,q}(t) \]  \hspace{1cm} (5)

\[ h_{l,j}(t) = \frac{1}{N} \sum_{n=1}^{N} \cos(2\pi f_{l,n} t + \phi_{l,n}) \]  \hspace{1cm} (6)

\[ h_{l,q}(t) = \cos\Omega \cdot h_{l,j}(t) + \sin\Omega \cdot \hat{h}_{l,j}(t) \]  \hspace{1cm} (7)

\( N \) represents the number of scattering paths, \( \hat{h}_{l,j}(t) \) Represents Hilbert transformation, \( \phi_{l,n} \) represents the initial phase of each branch and satisfies the random uniform distribution between \([0,2\pi)\).

\( f_{l,n} = f_{D_{\text{max}}} \cos\theta_{l,n} \) represents the Doppler frequency, \( f_{D_{\text{max}}} \) represents the max Doppler frequency, \( \theta_{l,n} \) indicates the incident angle of each signal, and \( \Omega \) represents a constant coefficient related to the shape of the power spectrum.

In the actual transmission process, there are multiple incident regions and the gain is different, so the above model is extended:

\[ h_l(t) = \sum_{i=1}^{M} k_i h_{l,i}(t) \]  \hspace{1cm} (8)

In the formula, \( k_i \) represents the gain factors of different incident regions are expressed and \( \sum_{i=1}^{M} k_i^2 = 1 \) is satisfied.

\[ h_{l,i}(t) = \sum_{n=1}^{N} c(f_{l,n} t) \cos(2\pi f_{l,n} t + \phi_{l,n}) \]  \hspace{1cm} (9)

\( c(f_{l,n} t) \) is expressed as the gain of different frequency points varying with time.

The time-average cross-correlation function of complex Gaussian stochastic processes can be expressed as follows:
\[ R_{hk,hk} (\tau) = \lim_{\tau \to \infty} \frac{1}{T} \int_{-T}^{T} \tilde{h}_i(t) \tilde{h}_k(t + \tau) dt = \]
\[ R_{hk,hk} (\tau) + R_{hk,hk} (\tau) + j[R_{hk,hk} (\tau) - R_{hk,hk} (\tau)] \]

(10)

The first term is the time average cross-correlation function between the same phase components of different complex Gaussian random processes.

\[ R_{hk,hk} (\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T}^{T} \sum_{l=1}^{N} c(l,t) \cdot \cos(w_{ln}t + \phi_{ln}) \cdot \sum_{m=1}^{N} c(l,t) \cdot \cos(w_{mn}(t + \tau) + \phi_{mn}) dt \]

(11)

According to the orthogonality of the trigonometric function, if and only if the Doppler frequency satisfies:

\[ w_{ln} = \pm w_{km}, \quad l \neq k, n \neq m \]

(12)

The formula can be reduced to \( R_{hk,hk} (\tau) = 0 \).

Therefore, the introduction of Doppler power spectrum does not affect the modeling process: When (12) is satisfied and \( \Omega = \pm \pi / 2 \), the complex Gaussian random processes generated by the extended model are independent of each other and have multi-interval partial U-shaped Doppler power spectrum.

**Figure 4.** Obtain the two paths’ frequency amplitude’s

**Figure 5.** Multi-path component distribution
Figure 4 shows the $w_n$ we obtained are different with each other, and Figure 5 shows that the Multi-path component amplitude’s distribution obeys Rayleigh distribution. Figure 6 shows the Doppler power spectrum is a part of U-shaped Doppler power spectrum, and Figure 7 shows the Doppler power spectrum is constant or slowly varies. Figure 8 shows the Doppler power spectrum quickly changes in sudden time.

![Figure 6. Doppler power spectrum](image1)

![Figure 7. Constant spectrum in time dimension](image2)

![Figure 8. Time-varying Doppler power spectrum](image3)
5. Simulation results
The discretion model of UAV near-ground communication channel is shown in the Figure 9. \( x(n) \) refers to the transmitted QPSK modulated signal, and \( y(n) \) refers to the received signal which has passed though the UAV near-ground communication channel. \( \tilde{h}_{\text{LOS}}(k) \) refers to the impulse response of the LOS path. \( \tau_k \) refers to the delay in different scatter path. And \( \tilde{h}_L(k) \) refers to different impulse response of scatter channel. The example system contains 100000 bits as the original message modeling by QPSK. And the parameters are set as follows: \( F_c \) is 1044MHz, the bit rate \( R_b \) is 5Mb/s, and the sampling frequency \( F_s \) is 10MHz. From COST-207, we assume the rural region value \( K_r = 6.9 \text{dB} \), the max value of delay \( \tau_{\text{max}} = 1 \mu s \) and \( \tau_{\text{slope}} = 0.11 \mu s \). The SNR of AWGN channel is \( E_b/N_0 \) from 0dB to 20dB. Figure 9 shows the discrete UAV near-ground communication channel. Figure 10 and Figure 11 show the scatter figures of received signal in different channels with different SNR. It’s obvious that the scatter figures in Figure 11 are much difficult to recognize QPSK signal than the same SNR in Figure 10. Figure 12 shows that just increasing the signal-to-noise ratio can not reduce the bit error rate in UAV near-ground communication channel.

\[
\begin{align*}
\tilde{h}_{\text{LOS}}(k) \\
\tilde{h}_L(k) \\
\tau_k \\
\tau_L(k) \\
\vdots \\
\sum
\end{align*}
\]

\[x(n)\rightarrow h_{\text{LOS}}(k)\rightarrow h_L(k)\rightarrow \tau_k\rightarrow \tau_L(k)\rightarrow \sum\rightarrow y(n)\]

**UAV near-ground communication channel**

**Figure 9.** QPSK signal transmitted through the multi-path channel

\[
\begin{align*}
E_b/N_0 = 0\text{dB} \\
E_b/N_0 = 10\text{dB} \\
E_b/N_0 = 20\text{dB}
\end{align*}
\]

**Figure 10.** The scatter figures of QPSK transmitted through AWGN channel with different SNR
Figure 11. The scatter figures of QPSK transmitted through multi-path channel with different SNR

Figure 12. The bit error rate curve

6. Conclusion

Through small-area modeling and analysis, the UAV near-ground communication multi-path channel is modeled as a complex Gaussian channel determined by Rice factor, time-delay power spectrum and time-varying Doppler power spectrum. The amplitude of the channel satisfies the Rayleigh distribution and the phase distribution satisfies the uniform distribution. When the UAV communicates with QPSK modulation, a large number of errors will be generated at the receiver, which is about power times of the AWGN channel. Therefore, the equalization of UAV near-ground communication channel is the focus of the next step. If the multi-path energy can be used to help transmit information, not only the bit error rate can be reduced, but also the signal-to-noise ratio gain can be obtained.

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