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Simulation Research on Transmission Performance of UAV Data Link in Multipath Channel

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Abstract. Low elevation Angle is the common working environment of Unmanned Aerial Vehicle (UAV) data link. Naturally, data link transmission performance will be affected by White Gaussian Noise (WGN). Besides, multipath interference is more characteristic and usually more harmful. Taking Phase Shifting Keying (PSK) modulation system commonly used in data link as the object and typical UAV data link point-to-point configuration as the prototype, this paper analyzes the transmission principle of this system and the characteristics of multipath channel transmission, and then establishes the simulated transmission model of measurement and control communication link in multipath channel on this basis. Through simulation experiment, part of the simulation data and conclusions are given. According to the paper, increasing the link level redundancy design is not the fundamental measure to solve multipath fading. And the paper suggests that in order to improve the transmission performance of data link in multipath channel, it is feasible to add adaptive equalization technology at the level of signal processing.

1. Overview

UAV data link is the nerve link between all nodes of UAV system and the key facility of integrated information platform of cross-domain unmanned systems [1-2], which has been widely used and continuously concerned in military, civil and commercial fields. PSK system is a transmission system which is commonly used in UAV systems and also a way of digital modulation with constant envelope. Due to its high power utilization and high band utilization, it is widely used to transmit command information and remote sensing information between unmanned air platform and ground command and control node. Owing to the particular working environment of UAV systems, such as aerial platform flight level is usually lower, for example ranging from several meters to thousands meters, which is too low compared with the distance ranging from tens of meters to hundreds of kilometer between UAV and ground node, so UAV usually work in a state of low elevation (e.g., 1 ° ~ 3 °). Besides, the surrounding environment is generally more complex, such as forest, mountain, near suburb or dense buildings, etc., leading to more severe multipath interference problems. This paper focuses on the PSK modulation system commonly used in UAV data link, establishes the channel transmission model of data link in multipath channel on the basis of principle analysis and analyzes the transmission performance under the condition of multipath channel through simulation, so as to provide reference for the evaluation of UAV system information transmission efficiency.

2. Principle Analysis

2.1. Introduction of Typical UAV Data Link Prototype System

Prototype system is the premise and foundation of simulation model. UAV data link has multiple configurations such as point-to-point, point-to-multi-point, multi-point to multi-point and ground-to-air network application [3-4]. In order to simplify analysis, this paper mainly establishes a data link channel transmission model based on point-to-point configuration. The typical prototype system of point-to-point UAV data link is shown in figure 1.

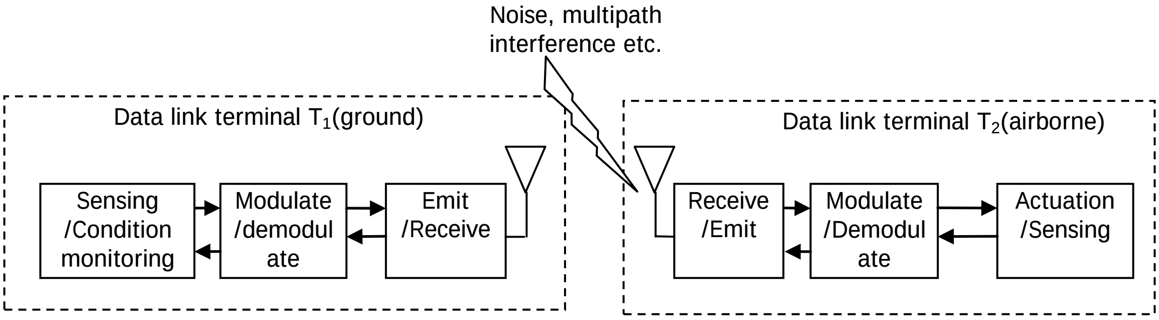

Figure 1. Typical structure of the prototype system of point-to-point UAV data link.

Figure 1 shows the prototype system of point-to-point data link configuration. The system consists of the ground data terminal (T1, Abbreviation GDT), which is generally adjacent to or unite with the ground command and control node of UAV systems, and the airborne data terminal (T2, Abbreviation ADT). The communication mode between T1 and T2 is commonly full duplex mode. Generally the T1 to T2 direction data link is called the uplink, and T2 to T1 direction data link is called the down link. Uplink usually apply PSK modulation, while down link usually apply QPSK modulation or other high order modulation and its basic communication principle is similar to uplink. Noise and multipath are the natural external interference between T1 and T2, which are different from the external artificial interference.

2.2. Principle Analysis of PSK Modulation System

The basic principle of PSK modulation system is shown in figure 2.

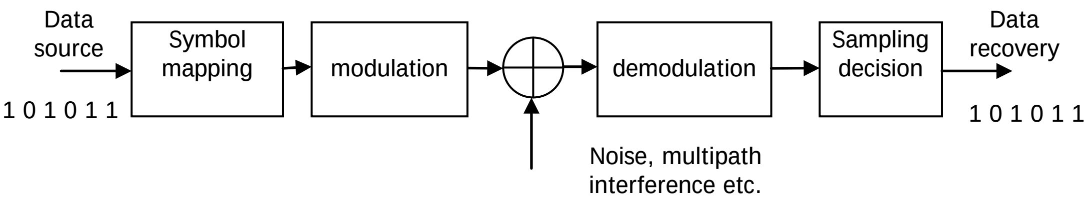

Figure 2. Basic principle of PSK modulation system.

In the figure 2, PSK modulation signal can be represented by equation (1), which is shown as

$$s(t) = A_c \cos(2\pi f_c t + \theta_c + \phi), \qquad 0 \le t \le T_b \tag{1}$$

In equation (1), A_C is the carrier amplitude, f_c is the carrier frequency, and θ_c is the initial phase of the carrier. ϕ is the modulation phase mapping of the data to be transmitted (binary symbol 0 or 1), there is the following phase mapping relationship:

$$\begin{array}{ll} '0', & \phi = \pi \\ '1', & \phi = 0 \end{array} \tag{2}$$

on the receiving end,

$$S_1(t) = A_c \cos(2\pi f_c t + \theta_c + 0) = \sqrt{2E_b/T_b}\cos(2\pi f_c t + \theta_c), \quad \text{symbol '1'}$$

$$S_0(t) = A_c \cos(2\pi f_c t + \theta_c + \pi) = \sqrt{2E_b/T_b}\cos(2\pi f_c t + \theta_c + \pi), \quad \text{symbol '0'} \tag{3}$$

In the equation above, T_b is the duration per bit and has $E_b = \frac{1}{2}A_c^2 T_b$.

PSK modulated signal passes through the Additive Gaussian White Noise (AWGN) channel with noise n(t), and when coherent detection is adopted, its theoretical error rate per bit is calculated as follows [5] :

$$P_b = Q\left[\sqrt{\frac{2E_b}{No}}\right] \tag{4}$$

In the equation (4), $Q(X) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-y^2/2dy}$; E_b is the energy per bit, and N_0 is the power spectral density (PSD) of the received input noise.

2.3. Analysis of Multipath Channel Transmission Characteristics

In general, the geometric relationship between airborne and ground data terminal antennas of UAVs data link is shown in figure 3.

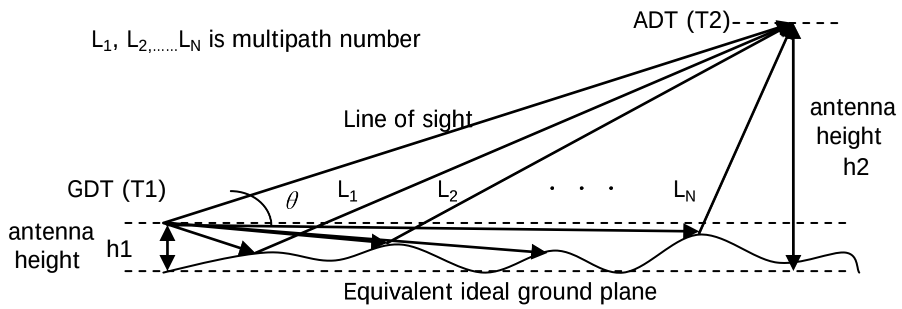

Figure 3. Geometric relation diagram of multipath channel.

In the figure, θ is the line-of-sight elevation angle between ADT and GDT. When θ ≤10°, the terminals in the data link are in the zone of low elevation angle. In addition to the line-of-sight main path component, there are more multipath components (i.e. L_1, L_2... L_N). At this point, assuming that Gaussian thermal noise n(t) is not considered, the signal at the receiving end is superposed by signal components from different paths including the main path, as shown in equation (5).

$$\begin{aligned} \mathrm{r}(t) &= \sum_{i=0}^{N} A_{ci}(t)\cos\left[2\pi f_c\left(t-\tau_i(t)\right)+\phi_c+\phi\right] \\ &= \sum_{i=0}^{N} A_{ci}(t)\cos\left[2\pi f_c t+\phi_c+\phi+\varphi_i(t)\right] \end{aligned} \tag{5}$$

In the equation (5), $A_{ci}(t)$ is the amplitude of receiving signals in the path i and $\tau_i(t)$ is the delay of receiving signals in the path i.

Usually, $A_{ci}(t)$ and $\tau_i(t)$ change slowly with respect to f_c, so multipath signal r(t) can be expressed as

$$\begin{aligned} r(t) &= \sum_{i=0}^{N} A_{ci}(t)\cos\varphi_i(t)\cos(2\pi f_c t+\phi_c+\phi) - \sum_{i=0}^{N} A_{ci}(t)\sin\varphi_i(t)\sin(2\pi f_c t+\phi_c+\phi) \\ &= X_c(t)\cos(2\pi f_c t+\phi_c+\phi) - X_s(t)\sin(2\pi f_c t+\phi_c+\phi) \\ &= V(t)\cos\left[(2\pi f_c t+\phi_c+\phi)+\varphi(t)\right] \end{aligned} \tag{6}$$

In the equation (6),

$$\begin{aligned} X_c(t) &= \sum_{i=0}^{N} A_{ci}(t)\cos\varphi_i(t) \\ X_s(t) &= \sum_{i=0}^{N} A_{ci}(t)\sin\varphi_i(t) \\ V(t) &= \sqrt{X_c^{\,2}(t)+X_s^{\,2}(t)} \\ \varphi(t) &= \arctan\left(\frac{X_c(t)}{X_s(t)}\right) \end{aligned} \tag{7}$$

According to equations (5) ~ (7), after transmission of PSK modulated signal through multipath channel, the originally determined carrier signal becomes a narrow-band signal with both envelope and phase modulated and also causes frequency dispersion in the spectrum.

The amplitude and arrival angle of the multipath signal are both random and statistically independent. When there is a main static signal component (the main path signal) between the receiving and sending ends, the envelope of the composite signal obeys the Rice distribution. In the Rice distribution, different multipath components are superimposed on the main line-of-sight (LOS) component, while the amplitude of other multipath signals is subject to the Gaussian distribution and the phase is subject to the uniform distribution from 0 to 2 π. When the main LOS signal component is lower than the multipath components or has been submerged in the multipath components, the envelope of the superimposed signal obeys the Rayleigh distribution, the amplitude of each multipath component obeys Gaussian distribution, and the phase obeys the uniform distribution from 0 to 2 π[6-7].

Typically, the main signal component is stronger than multipath signal components in the LOS data link of UAV communication and generally the multipath channel presents the characteristics of Rice channel. However, under several special circumstances, the main signal component will be submerged in the multipath signal components. In this case, the transmission channel presents the characteristics of Rayleigh channel.

3. Establishment of Multipath Channel Transmission Simulation Model

Refer to Figure.1, UAV data link is easy influenced by modulation and demodulation procedure in the signal processing. At same time the antenna will also bring in external noise and various interference factors including multipath. Therefore, the transmission simulation analysis model under multipath channel is established as shown in figure 4.

Data source module outputs binary data flow $d_0(t)$ (0 or 1). Data flow goes through the symbol constellation mapping and converts to binary non-return to zero data flow d(t) (-1 or 1, respectively corresponding to phase π or 0). In order to reduce intersymbol interference and compress transmission bandwidth, the shaping filter is added. And then after PSK modulation, we get the modulation signal s (t). After going through multipath channel or/and AGWN channel, s(t) reaches the receiving demodulation end. When receiving signal r(t) only considers the multipath case, its signal form is expressed by equation (5). When simultaneously superposing Gaussian noise n(t), n(t) should be added to equation (5). When the influence of multipath signal is not considered, n(t) can just be added to equation (3). r(t) is demodulated in the PSK demodulation module and then delivered to the receiving filter module, going through the integral reset and sampling decision procedure and outputting d '(t) code stream. Then the code stream turns to binary data stream $d'_0(t)$ after symbol inverse mapping or constellation map inverse transformation procedure.

In figure 4, PSK modulation adopts the coherent demodulation method. However, since synchronization of the carrier at both ends of the transceiver is not the focus of this paper's simulation, we simplify the simulation model without obviously affecting the simulation result of the transmission performance. It is assumed that the carrier at both ends of the data link is already in synchronization when the link is established. Meanwhile, data link transmission delay should be considered when comparing BER between the data resource $d_0(t)$ and recovered data flow $d'_0(t)$. The original data delays forτ_d value which can be acquired through the cross-correlation of $d_0(t)$ and $d'_0(t)$).

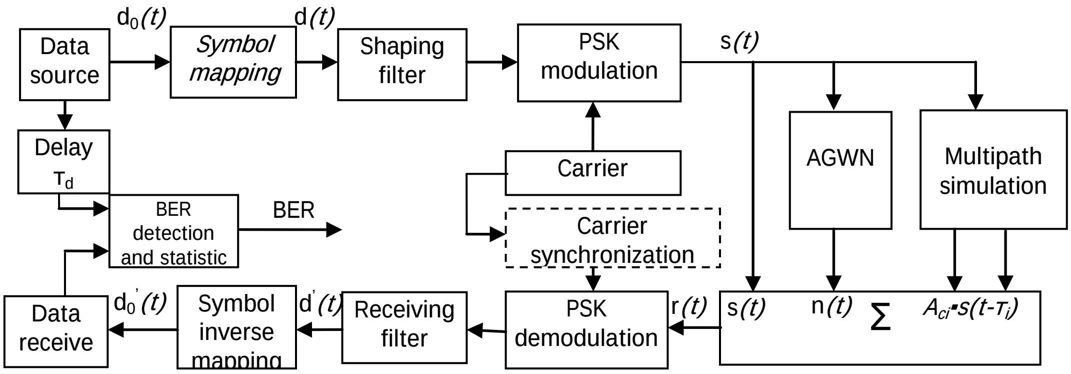

Figure 4. Multi-path channel transmission simulation model of UAV data link.

4. Simulation and Result Analysis

4.1. Simulation Environment and Related Parameters

According to the simulation model of multipath channel data link transmission shown in figure 4, the simulation circuit is built in the System Vue environment. Main parameters are set as follows

Table 1. Simulation environment and related parameters.

Type	Data rate R_b (Mbps)	Modulated carrier frequency f_c(GHz)	Modulation method	Shaping filter type	Number of multipath signal
Parameter	1.024	1.6	PSK	Raised cosine roll-off, roll-off factor: 0.5	1 path of main signal, 1 path of adjustable multipath signal, adjustable delay, random phase

There are many multipath paths in the workplace of data link, and it is impossible and meaningless to exhaust them in simulation. And usually it is the strongest multipath signal that has the greatest influence on transmission performance. In addition to the amplitude A_i (or signal Power P_i) of this multipath signal, the transmission delay τ_i of the signal and random change of carrier phase which is caused by multipath will also have an effect on the quality of the received signal. In order to simplify the complexity of simulation, this paper only includes 1 path of main signal and 1 path of multipath signal which has the maximum signal strength.

4.2. Simulation and Result Analysis

In the first step, modeling and simulation experiments are carried out to analyze the receiving and demodulation performance under the situations of several signal noise power spectral density ratios. Figure 5-7 show the baseband receiving signal eye diagram when E_b/N_0 = 5, 8 and 11dBHz, respectively.

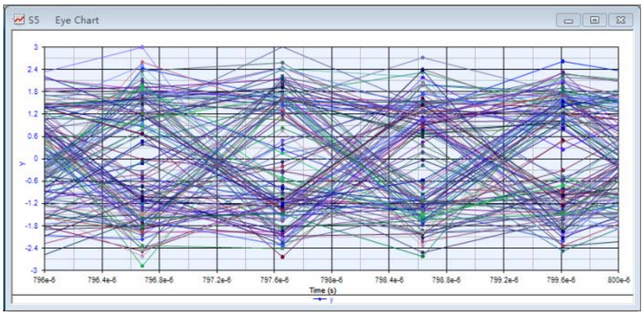

Figure 5. Baseband signal eye graph of receiving end when E_b/N_0=5dBHz.

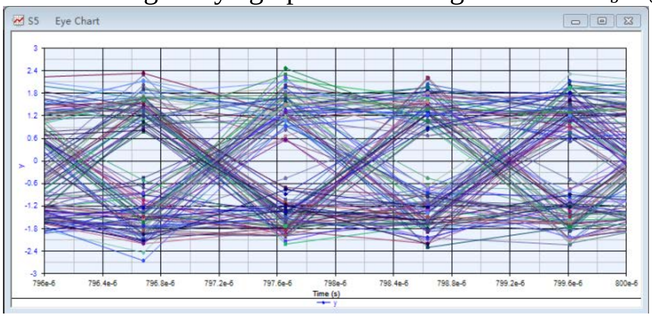

Figure 6. Baseband signal eye graph of receiving end when E_b/N_0=8dBHz.

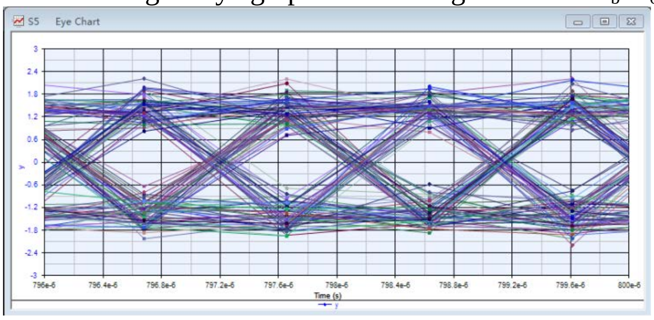

Figure 7. Baseband signal eye graph of receiving end when E_b/N_0=11dBHz.

Figure 8 shows the superposition graph of the simulated BER curve and the theoretical BER curve when Eb/N0 = 1,2…10 dBHz.

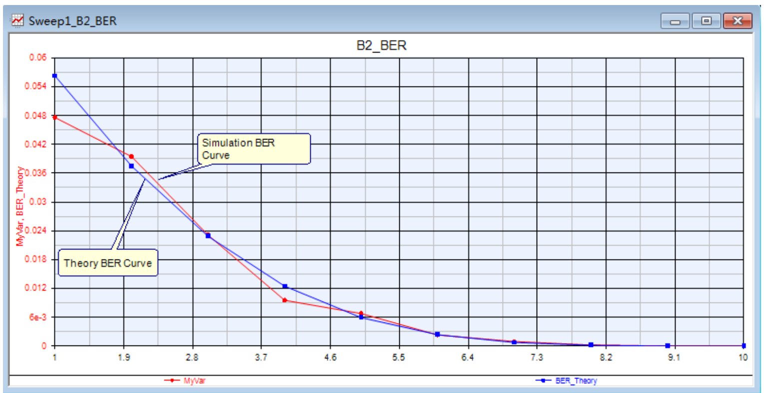

Figure 8. Superposition curve graph of simulated BER and theoretical BER.

According to the simulation results shown in figure.5-8, this paper simulates the transmission performance of the simulation model under AGWN channel, and verifies the correctness and effectiveness of the simulation model.

The second step, we change the AGWN channel to multipath transmission channel, and set the multipath fading factor G_i and multipath transmission delayτ_i. The multipath channel carrier phase obeys the uniform distribution from 0 to π and will be generated randomly by the function in the simulation model. Figure 9-13 show the comparison graph of the quality of receiving signal under different fading conditions when PSK modulation signal goes through multipath channel with transmission delay τ_1=4T_b and carrier phase φ_1 randomly changed, which is shown in the form of eye graph.

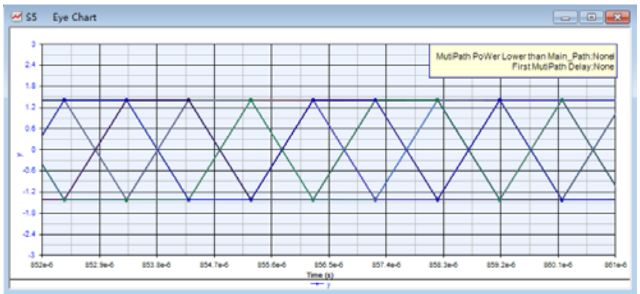

Figure 9. Eye graph of baseband signal at receiving end without multipath component.

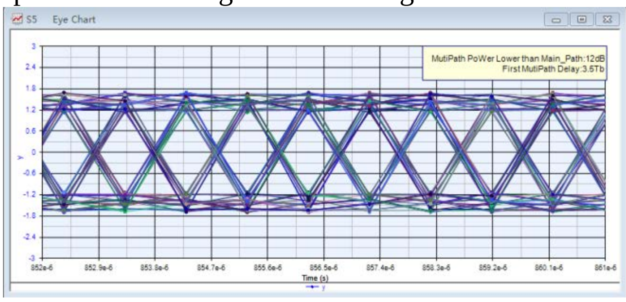

Figure 10. Eye graph of baseband signal at receiving end when the power of multipath signal is 12dB lower than the power of main signal.

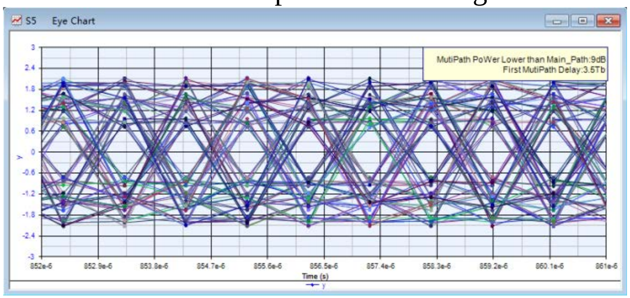

Figure 11. Eye graph of baseband signal at receiving end when the power of multipath signal is 9dB lower than the power of main signal.

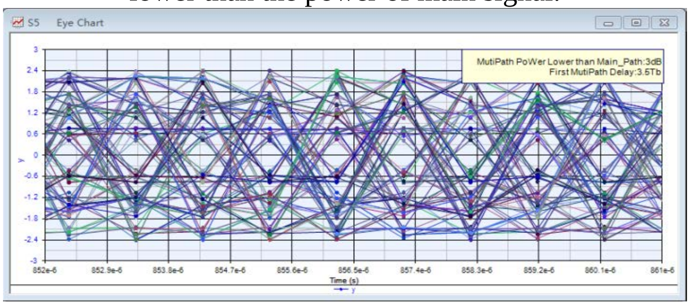

Figure 12. Eye graph of baseband signal at receiving end when the power of multipath signal is 6dB lower than the power of main signal.

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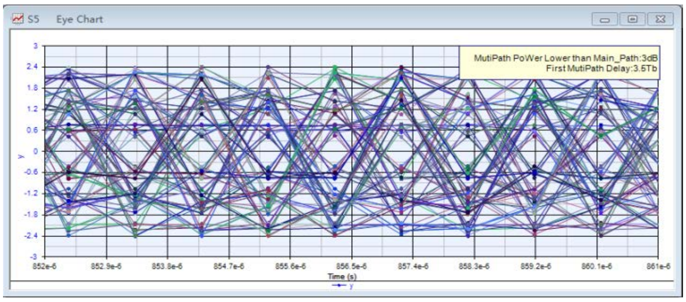

Figure 13. Eye graph of baseband signal at receiving end when the power of multipath signal is 3dB lower than the power of main signal.

As can be seen from figure 9-13, with random phase of multipath signal increasing and determined time delay, signal quality deteriorates significantly. When the power of multipath signal is 3dB lower than the power of main signal, eye diagram is nearly closed. At this time, the quality of received signal is too poor to effectively recover the data.

Figure 14-17 respectively simulate the quality of received signal when multipath reflection coefficient is fixed and the phase is random while multipath time delay changing within a certain range. Figure.18 is the spectrum graph of the transmitted signal at the modulating transmitting end. Figure.19 is the spectrum graph of the multipath superposed signal at the receiving end when the power of maximum multipath signal is 6dB lower than the power of main signal, the phase is random and the delay is $2.4T_b$.

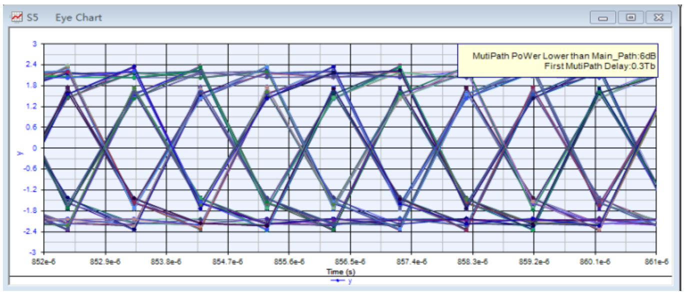

Figure 14. Eye graph of baseband signal at receiving end with multipath power lower 6dB than main path and delay of $0.3T_b$.

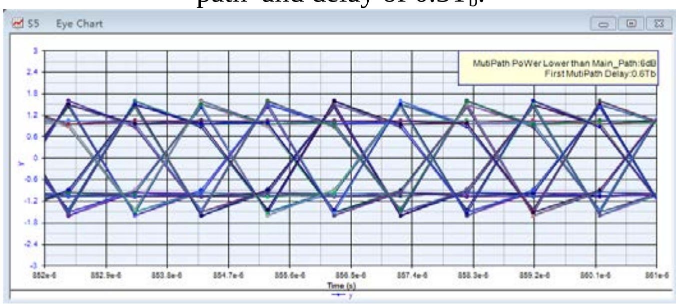

Figure 15. Eye graph of baseband signal at receiving end with multipath power lower 6dB than main path and delay of $0.6T_b$.

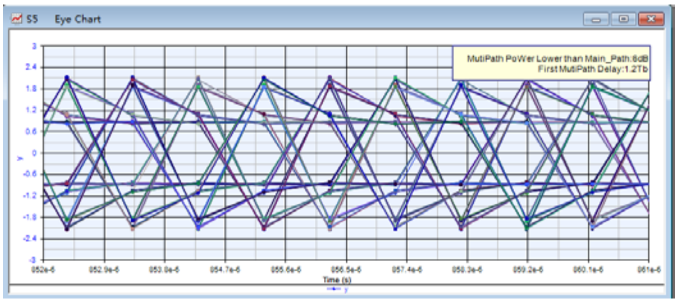

Figure 16. Eye graph of baseband signal at receiving end with multipath power lower 6dB than main path and delay of 01.2T$_b$.

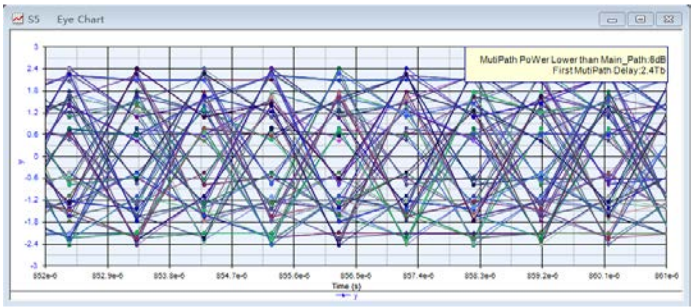

Figure 17. Eye graph of baseband signal at receiving end with multipath power lower 6dB than main path and delay of 2.4T$_b$.

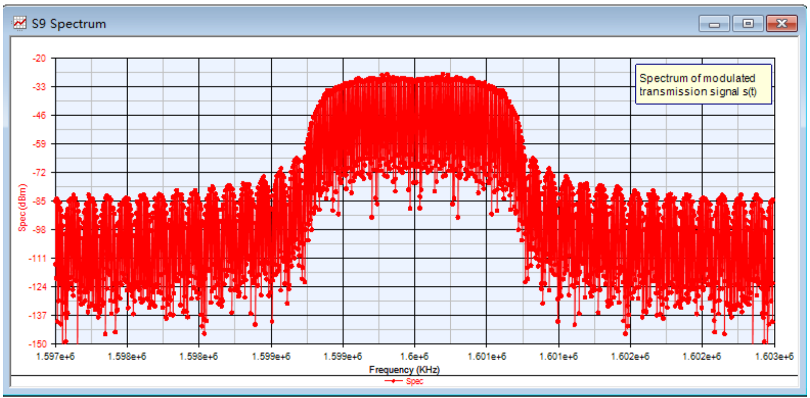

Figure 18. Spectrum of modulated and transmitted signal.

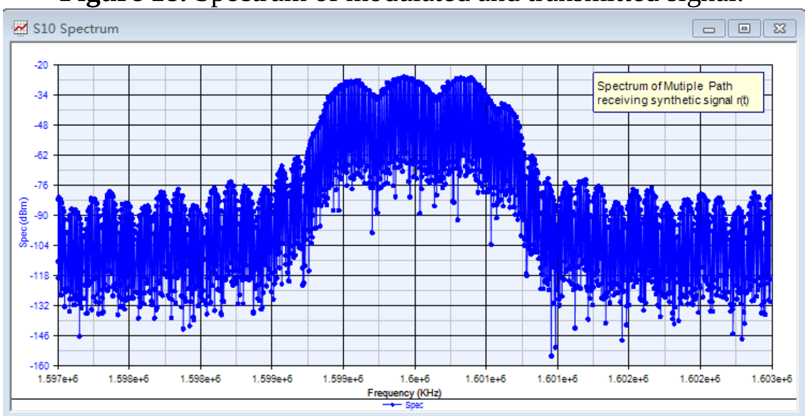

Figure 19. Spectrum of multipath superposed signal at the receiving end.

According to the simulation process and the data shown in Figure.14-19, the analysis shows that when the multipath time delay is within the range of 0-0.5T_b, the eye graph is relatively ideal, and it is generally not affected by random phase changes. In the case that the amplitude of multipath signal declines at a certain level and the multipath time delay is within the range of 0.5T_b-1T_b, the eye graph deteriorates greatly, but it is slightly affected by random phase changes. When the multipath time delay is greater than one T_b, the eye graph becomes significantly worse and is greatly affected by the random phase changes. At this time, the spectrum of the multipath superposed signal presents multi-peak state.

5. Conclusion

In this paper, the transmission performance of UAVs' data link under multipath channel is simulated by modeling the common modulation system with main working parameters, and some simulation test data are presented. According to the simulation process and result, the author thinks in UAV data link, the link level redundancy design for AGWN channel is effective. In view of multipath channel, because of the link level redundancy design, not only has the main signal been increased, but also has the multipath signal at the receiving end been increased. That is to say, the past view that the link level redundancy design is mainly aiming at multipath fading is obviously not entirely correct. In addition to the data link modulation system, spread spectrum modulation and/or adaptive equalization in signal processing should be the basic measures to improve the anti-multipath interference of UAV data link [8-9].

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