Multi-Channel Access in Ultraviolet Space Optical Communication

Yanfeng Tang, Hongzuo Li and Bailiang Huang

Abstract—Space optical communication have some special advantages, such as high degree of confidentiality, large information capacity. It has been the research hotspot in the field of wireless communication. But it is strict with link and weather because of the communication mode that point to point. It limits the application of space optical communication. Ultraviolet (UV) communication is different from other optical communication methods. The UV is transmitted with scattering principle in atmospheric. So, it is suitable for Non-Line- of -Sight communication. But it is limited that the communication distance because the received energy attenuation is serious. Moreover, the signals will interfere with each other when they reach the receiver which are transmitted from multipath because of atmospheric scattering. It will lead to the high bit error rate of the UV communication. In this paper, it is presented that the multiple access technology of ultraviolet which uses the multipath effect. The main goal of the technology is to improve receiving total energy and increase the communication distance of ultraviolet communication. Meanwhile, it is solved that the signal interference when multipath signal reach the receiver. The ultraviolet communication will be applied extensively in the wireless network, emergency communication, sensor communication system, with the unique advantages of non-line-of-sight transmission and all-weather work.

Keywords—Ultraviolet optical communication, Multipath effect, Multi-channel access, Receiving power.

I. INTRODUCTION

Space laser communication is a hotspot in the field of wireless communication due to its advantages such as good confidentiality, large information capacity and fast transmission rate. However, the general space optical communication is point-to-point communication mode. It is strict with link. It is required that the precise alignment between the two parties, so it is usually required that the high precision mechanical alignment device in space optical communication system. General space optical communication is severely affected by the weather, such as rain, snow and fog. It can affect the communication and even lead to communication interruption.

The ozone layer has a strong absorption effect on the UVC band ultraviolet light of 200-280nm. In the near atmosphere, there is almost no natural ultraviolet radiation source in the UVC band (so called solar blind area), which makes the UVC band ultraviolet optical communication system have the following advantages [1-3]:

(1) NLOS transmission. The ultraviolet light propagates in the form of strong Rayleigh scattering in space, which overcomes the difficulty of strict alignment between the transmitter and receiver of infrared communication and enhances the mobility and flexibility of the communication system.

(2) Ultra-low background noise. The solar blind band background noise caused by solar radiation is almost zero near the ground surface. The receiver can adopt a detector with high sensitivity, and a wide field of view optical antenna is installed in front of the detector, which can greatly improve the receiving performance.

(3) All-weather work. Ultraviolet optical communication will be affected by the geographical environment, climate and weather conditions, which has certain influence on communication distance and performance, but still can basically guarantee all-weather work.

At present, the study of ultraviolet communication is on the stage of theoretical basis, because it is limited by atmospheric scattering when the UV light is transmitted in the atmosphere [4].

The communication distance is limited because of the power loss. The transmission rate is effect because of multipath effect.

But also due to the reason of UV light transmitting through atmospheric scattering, result in that UV light appears multi-path effect in the transmission process. And the serious absorption and loss property of atmosphere on UV light makes the receiving optical signal power very weak, which limits the UV optical communication distance. On account of the multipath effect in UV optical space transmission, this paper proposes a multi-channel technology, which can effectively solve the problem of low receiving power.

II. TRANSMISSION MODEL OF ULTRAVIOLET LIGHT SCATTERING

At present, the ultraviolet NLOS optical communication

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channel model mainly adopts single scattering model, and this model based on ellipsoidal coordinate system can calculate the channel loss, impulse response and delay characteristics of transceiver at different positions. However, the model ignores the influence of multiple scattering, so that the calculation error is relatively large in long distance communication or under complex climate condition. So, this paper adopts a multiple scattering model based on Monte Carlo method on the basis of single scattering model [5-8]. The geometrical structure of NLOS ultraviolet optical communication is shown as Fig. 1.

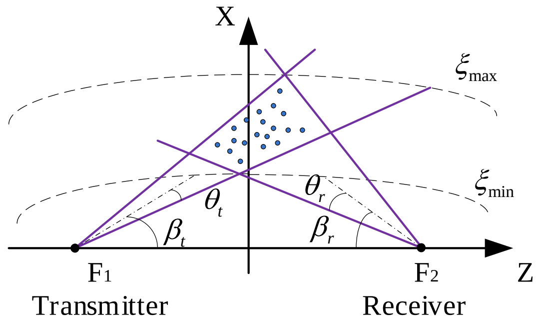

Fig. 1. Geometric structure of NLOS ultraviolet optical communication

In Fig. 1, R is the linear distance between the transmitter and the receiver. β_t and β_r are elevation of the transmitter and the receiver respectively. θ_t and θ_r are respectively beam angle of the transmitter and field angle of the receiver. V represents the volume of scatters, and the distance from any point in V to the receiver and transmitter is respectively r1 and r2.

It can be deduced that the signal energy E_r transmitted to the receiver detector through the atmospheric channel is given as,

$$E_r = \frac{E_t c k_s P(\mu) A_r}{\Omega_t r} \int_{\xi_{\min}}^{\xi_{\max}} \int_{\eta_1(\xi)}^{\eta_2(\xi)} \int_{\phi_1(\xi,\eta)}^{\phi_2(\xi,\eta)} \frac{2\exp(-k_e r \xi)\cos(\xi)}{\xi^2-\eta^2} d\phi d\eta d\xi \quad (1)$$

Where E_t is the transmitting pulse energy of the transmitter, c is the speed of light, k_s is the scattering coefficient, $P(\mu)$ is the scattering phase function, A_r is the receiving aperture area of the detector, Ω_t is the cone angle of the transmitter beam. ξ, η and ϕ respectively represent radial coordinates, angular coordinates and azimuth coordinates of ellipsoidal coordinate system. The scattering phase function, A_r is the receiving aperture area of the detector, Ω_t is the cone angle of the transmitter beam. ξ, η and ϕ respectively represent radial coordinates, angular coordinates and azimuth coordinates of ellipsoidal coordinate system. The Monte Carlo method can better solve the problem of NLOS optical transmission calculation by directly tracing the transmission process of photon in the medium, which is a direct photon tracing method, so it has weak dependence on the calculation conditions and has the advantage of strong adaptability.

The simulation steps of the multiple scattering channel model based on Monte Carlo method are shown as Fig. 2.

The Monte Carlo method is a simulation method based on random process, which can be used to study the line-of-sight and non-light of sight transmission about single scattering and multiple scattering.

In direct Monte Carlo method, the amount of photons that reach the detector finally is less because photons are randomly walking and the detector's area is lesser. Most of the photons do not have contribution to the detection result. In order to get stable results, it is only to simulate a large number of photons, but it will increase the running time of the program.

The basic steps of the multi-scattering model based on Monte Carlo method:

①Emitting photon, it is to stipulate its field scope and give initial weight.

②It is to determine the next collision point. The method is to sample the random step length of the photon in the atmospheric transport and calculate the change of the photon weight.

③ It is to select the direction of the photon collision according to the scattering phase function.

④It is to determine whether to stop tracking photons. It can be regard as photon death when the photon weight is less than the set threshold or escape from the receiving field, the photon is not traced.

⑤It is to calculate the probability of received photon and measure the detection probability of detector after scattering.

It is improved based on the basis of Monte Carlo method and simulated based on directed probability method. It can be obtained through simulation that the result of directed probability method is consistent with direct Monte Carlo method and single scattering. The efficiency improves a lot.

It is an ideal situation that the axis of the cone of transmitter and receiver are coplanar. It is very difficult to make the axis of the cone of transmitter and receiver coplanar in the actual application. If analyze problem with ideal model , it will affect the impulse response and energy detected by the detector because it affects the scattering volume.

Based on the model of non-line-of-sight ultraviolet light transmission, it is simulated that coplanar and non-coplanar of sending and receiving axis. It is mainly researched that the impulse response and energy density detected by detector.

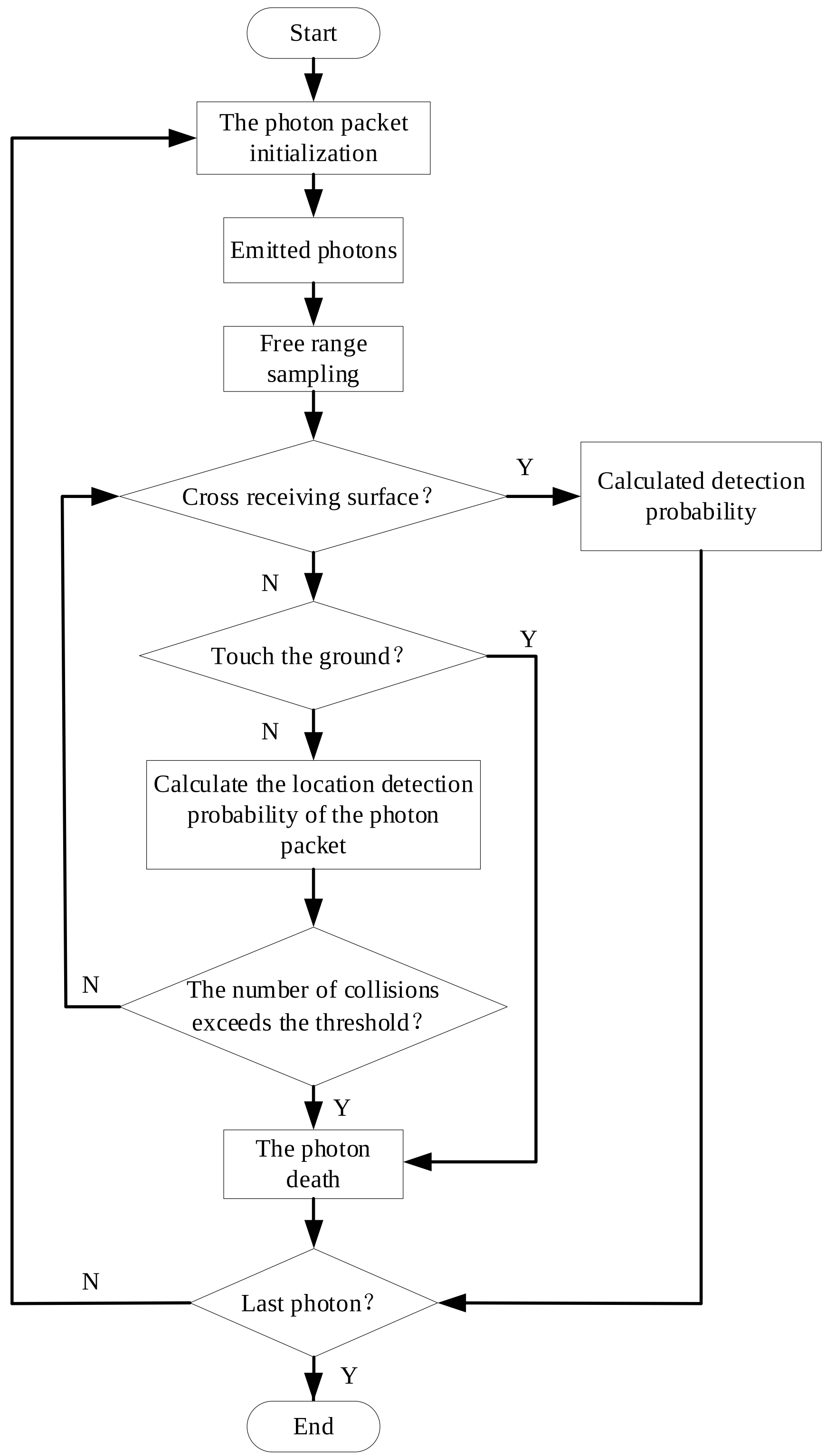

Fig. 2. Simulation steps of multi scattering channel model based on Monte Carlo method

It is shown through the simulation results, that angle of elevation is closer to PI/2, the affect that angle of deflection to result is more less. With the increase of detection target's distance, the effect that the deflection angle of the emission axis to result decreases gradually.

The impact that the Transmitting deflection Angle response to detector is shown in Fig. 3. It can be seen from (a), that the impulse response delay is close when the distance is long between transmitter and receiver, and the peak of impulse response decreases with increasing of the deflection angle

Compared with (c) and (d), it can be known that, when the distance between transmitter and receiver is closer, the impulse response delay will increase and the peak will decrease with the increase of the deflection angle. The pulse delay is larger, the pulse width is wider and the peak is larger when launch half angle is smaller. It is large that the impact of deflection angle to detection when detected distance is short. It is small that the impact of deflection angle to the impulse response [9].

$$\frac{t_d}{1/R_b}=\frac{R_b\bullet[(h_2/\sin\theta_3+h_2/\sin\theta_4)-L]}{c} \quad (3)$$

Among them, c is the speed of light, R_b is the optical pulse rate, and other parameters are shown in the Fig.4. When the

pulse delay reaches a certain degree, it will generate the intercoder interference, lead to the multipath effect.

(2) Multipath channel fading

Channel fading of non-visual ultraviolet communication has two ways of fast fading and slow fading. The slow fading is the representation that the local mean value of signals with time variation. It is the intensity scintillation caused by atmosphere

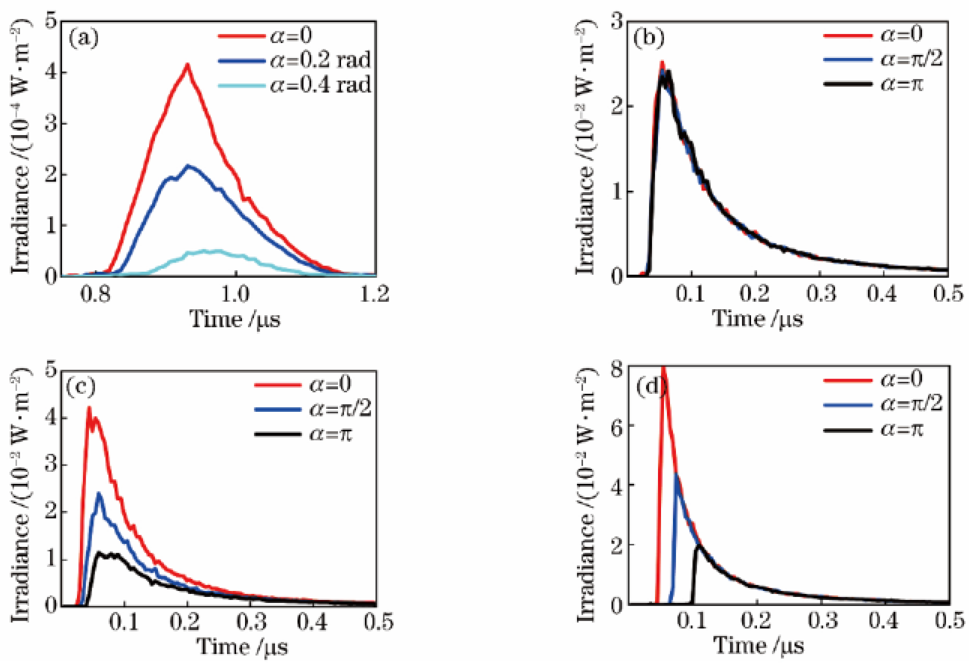

Fig.3. Pulse response under different conditions

III. Multi-Channel Access Technology

Ultraviolet optical communication uses atmospheric scattering principle to produce multipath transmission effect. Based on the characteristics of multipath transmission, the MIMO technology in communication is used for reference.

(1) Multipath effect

The multipath effect is mainly caused by atmospheric scattering in UV space optical communication system. The signal from transmitter divided into multiplex because of multipath effect. The signals arrive the receiver on different time because the length of every path is different. It will lead to pulse delay. The scattering condition is shown in the Fig. 4., the pulse delay width is as follows:

$$\frac{t_d}{1/R_b}=\frac{R_b\bullet[(r_1+r_2)-L]}{c}=\frac{R_b\bullet[(h_1/\sin\theta_1+h_1/\sin\theta_2)-L]}{c} \quad (2)$$

turbulence. The fast fading is essentially caused by the phase difference of the received signal component. It is produced by the multiple transmitting signals received with minute delay. So, it can also be called multipath fading.

The phase characteristics of receiving signals in multipath fading are characterized by frequency domain characteristics, time domain characteristics and spatial domain characteristics. The time domain characteristic is corresponded to delay expansion or frequency selective fading, and it is caused by the received signal waveform broadening because of intersymbol interference. the spatial characteristic is corresponded to the angle expansion or spatial selective fading, and it means that the angle of arrival of multipath signal is broadened when reach the receiver. Total fading is the product of two fading. In ultraviolet communication, it is adopted that the intensity modulation and direct detection, and the receiver is photoelectric conversion process. So ultraviolet communication is generally not considered in space and time selective fading selective fading.

(3) Theoretical research on multi-channel access

technology. According to the theory of wireless communication, wireless communication performance depends on the fading effect. The most direct method of improving the receiving optical signal energy at receiver is to increase the transmitter energy or to increasing the receiving area of the antenna. While the greater

the transmitting power is, the greater the interference to surrounding environment or equipment will be. Meanwhile, increasing receiving antenna area will affect communication system flexibility and the receiving performance is not improved obviously. Based on the characteristics of atmospheric scattering multipath transmission of ultraviolet NLOS optical communication and referring to the idea of diversity reception in wireless communication system, this paper puts forward the multi-channel access technology of ultraviolet communication, which can overcome the influence of multipath effect caused by atmospheric fading, improve the channel reliability and increase the communication distance under the condition of without increasing the transmitting power and with the same system bandwidth. There are three kinds of merging techniques which includes optimal selection combining, equal gain combining and maximum ratio combining. And the output signal-to-noise ratio (SNR) of the three merging techniques is as follows.

① Optimal selection combining

The optimal selection combining technique is the simplest to design and easier to implement among the three merging methods. The output SNR is given as [10],

$$\mathrm{SNR}_{\mathrm{OSC}} = \max\left\{\mathrm{SNR}_1, \mathrm{SNR}_2, \cdots, \mathrm{SNR}_{N_r}\right\} \tag{4}$$

Where $\mathrm{SNR}_i \ (i = 1, 2, \cdots N_r)$ is the SNR of the i_{th} diversity branch. In this way, only one road communication power is received and other roads are discarded, so it is not the best combining method.

② Maximum ratio combining

The maximum ratio combining technique demodulates and analyzes the receiving signal from different paths, and the gain coefficients are assigned to the signals by gain variable amplifiers. When the weight of the j_{th} branch is taken as $w_j = x_j / N$, the output $\mathrm{SNR}_{\mathrm{MRC}}$ of the MRC combiner is the largest, and it can be expressed as

$$\mathrm{SNR}_{\mathrm{MRC}} = \frac{1}{2}\sum_{j=1}^{N_r}\frac{x_j^2}{N} = \sum_{j=1}^{N_r}\mathrm{SNR}_j \tag{5}$$

Where x_j is the instantaneous useful signal of the j_{th} branch, and $N = N_0/2$, where N_0 is the single side noise power spectrum density.

③ Equal gain combining

The equal gain combining does not need to cope with signal weighing. The signal of each branch is added with equal gain. In this method, each diversity branch signal is processed in-phase, and then superimpose, that is $w_j = 1\,(j = 1, 2, \cdots N_r)$. The output SNR of the EGC combiner is given as,

$$\mathrm{SNR}_{\mathrm{EGC}} = \left(\frac{x^2}{2}\right) N_r N = \left[\frac{\left(\sum_{N_r}^{j=1} x_j\right)^2}{2}\right] N_r N \tag{6}$$

It can be seen from the formula (6) that the average SNR obtained by equal gain combining method is approximately proportional to the number of diversity branches N_r. The three merging methods can be simulated by MATLAB, assuming the average SNR of each receiving branch is $\mathrm{SNR}_C = 8\mathrm{dB}$, the performance curve of each method is shown as Fig.5.

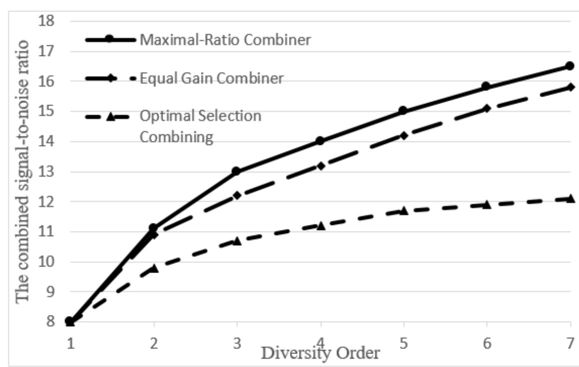

Fig. 5. Receiving performance curves under different merging methods

It can be obtained by comparing the performance curves of the three methods that, under the same diversity order, the improvement of SNR performance of maximum ratio

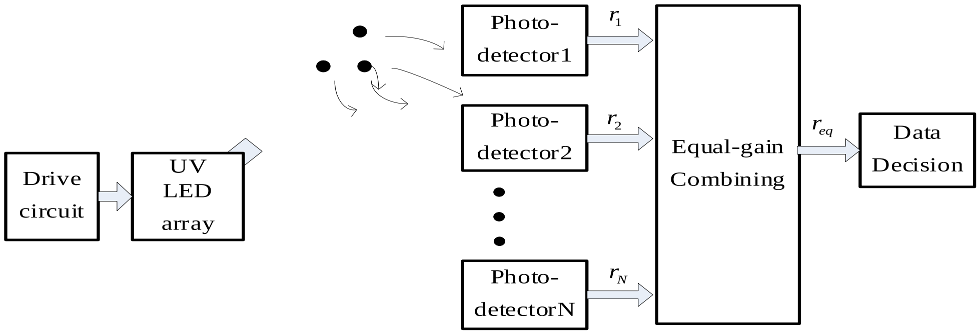

Fig. 6. Schematic diagram of multi-channel signal access model

combining method is the best, followed by that of equal gain combining method. When the diversity order is lower, the performance of equal gain combining is close to the maximum ratio combining, and the optimal selection combining is the worst. Moreover, the performance of equal gain combining is not the best among the three merging methods, but its implementation complexity is lower, which is a more practical merging method. And this method is applied in the MIMO system of this paper.

(4) Multi-channel signal access modeling

Diversity reception is a technical measure to compensate fading channel loss. It usually takes advantage of irrelevant features between independent samples of the same signal in the wireless propagation environment and adopts a certain signal merging technology to improve the quality of receiving signal, in order to resist the adverse effects caused by channel fading, which can greatly improve the reliability of multipath fading channel transmission. The multi-channel reception model of ultraviolet optical communication is shown as Fig. 6.

Suppose the multi-channel reception has N branches, r_i represents the signal amplitude of the i_{th} branch, r_{eq} represents the signal amplitude after equal gain combining and it can be expressed as,

$$r_{eq} = \sum_{i=1}^{N} r_i \tag{7}$$

Under the condition of weak fluctuation turbulent atmosphere, let the mean value of the log amplitude x is $\langle x \rangle$ and the variance is σ_x^2, we can get,

$$P_x(x) = \frac{1}{\sqrt{2\pi}\sigma_x} \exp\left\{ -\frac{(x - \langle x \rangle)^2}{2\sigma_x^2} \right\} \tag{8}$$

If the amplitude $A = A_0 \exp(x)$, the probability density function of $I = A^2$ can be obtained by probability transformation,

$$P_I(I) = \frac{1}{2\sqrt{2\pi}\sigma_x I} \exp\left\{ -\frac{\left(\ln\left(\frac{I}{I_0}\right) - 2\langle x \rangle \right)^2}{8\sigma_x^2} \right\} \tag{9}$$

Where I represent the receiving light intensity and I_0 is the average receiving light intensity.

The communication conditions are set as follows: in the near atmospheric level link, the transmission distance z is respectively 1.2km and 10.4km, the number of transmitting light beam is respectively 1, 2, 4, 8, 16, and receiving antenna diameter is 5.1cm. The probability density function of the receiving light intensity fluctuation caused by the turbulence effect is shown as Fig. 7 and Fig. 8.

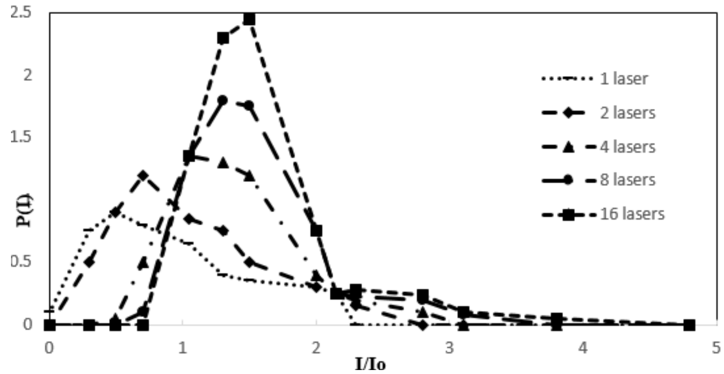

Fig. 7. Probability density function of receiving light intensity fluctuation under different number of beams (z=1.2km)

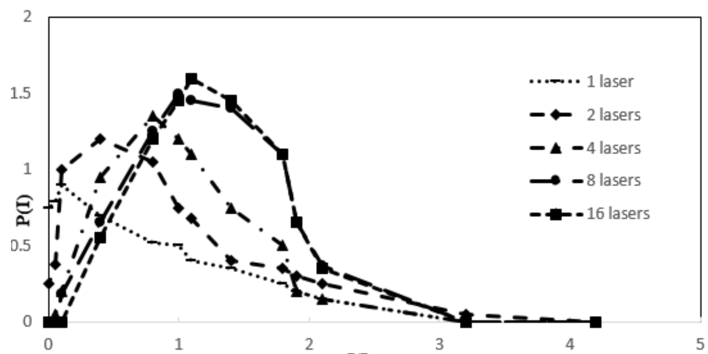

Fig. 8. Probability density function of receiving light intensity fluctuation under different number of beams (z=10.4km)

It can be obtained from the two graphs above that the light intensity fluctuation decreases with the increase of the number of beams. Comparing the two graphs, it can be found that the light intensity distribution of the transmission distance of 1.2km is far better than that of the transmission distance of 10.4km, and the light intensity fluctuation variance of the former is far less than that of the latter. If single beam is transmitted, it can be seen from the graphs, the intensity fluctuation is very large, and the curves are close to the negative exponential distribution. With the increase of the number of transmitting beams, the curve is getting closer to the lognormal distribution.

IV. Multi-channel Receiving System

(1) OFDM modulation of light

In the optical OFDM system, the delay of the pulse is absorbed by the protection interval of OFDM signals. In the transmitter, the signal sequence is changed into N parallel symbol through the conversion between serial signal and parallel signal. Modulated parallel symbol is changed into a set of N different subcarriers. and then plus the protection interval. OFDM signal is generated. The signal passed the bandpass filter is changed into light intensity signal through driving the optical source. The light intensity signal is converted into an electrical signal through the photodetector at the receiving end. The original signal is restored after OFDM demodulation. The functional block diagram of optical OFDM system is shown as Fig. 9.

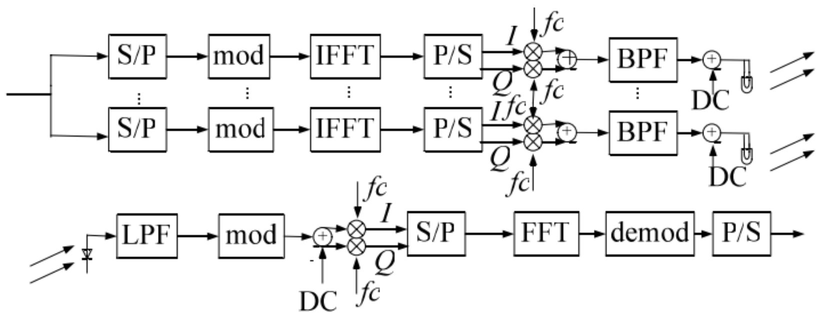

Fig. 9. Block diagram of optical OFDM system

(2) The receiving end of the ultraviolet NLOS optical communication system transforms the received weak light signal into electrical signal, then using FPGA processor for signal processing, filtering and recovery decision [11-12]. The photoelectric detector converts the optical signal into current signal, then FPGA converts the current signal into voltage signal. So the current signal can be amplified as voltage signal using the transimpedance amplifier.

Considering the analog signal is vulnerable to interference and other issues, the following receiving scheme is adopted in order to improve the reliability and accuracy of the system. After the output analog current signal of the photodetector PMT passing the transimpedance amplifier, the voltage signal is sampled and quantized, and FPGA is utilized for filtering the quantized signal and diversity reception combining processing, then the next is decision and recovery. The design scheme diagram is shown as Fig. 10.

V. Conclusion

Ultraviolet optical communication is different from other wavebands optical communication, which can realize NLOS transmission by making use of atmospheric scattering. However, due to the serious channel fading, result in that the receiving power of receiver is low and communication distance is short.

(1) It is analyzed that the OFDM modulation system. The communication system performance of OFDM modulation system without guard interval is enhanced slightly than OOK modulation system. The communication system performance of OFDM modulation system with guard interval is enhanced greatly than OOK modulation system and OFDM modulation system without guard interval. The ultraviolet light signal has multipath effect when it is transmitted in free space because the atmospheric scattering. It will produce signal delay when the multi-channel signals arrive the receiver. It can effectively suppress the multipath effect and improve the communication quality because of OFDM modulation system with

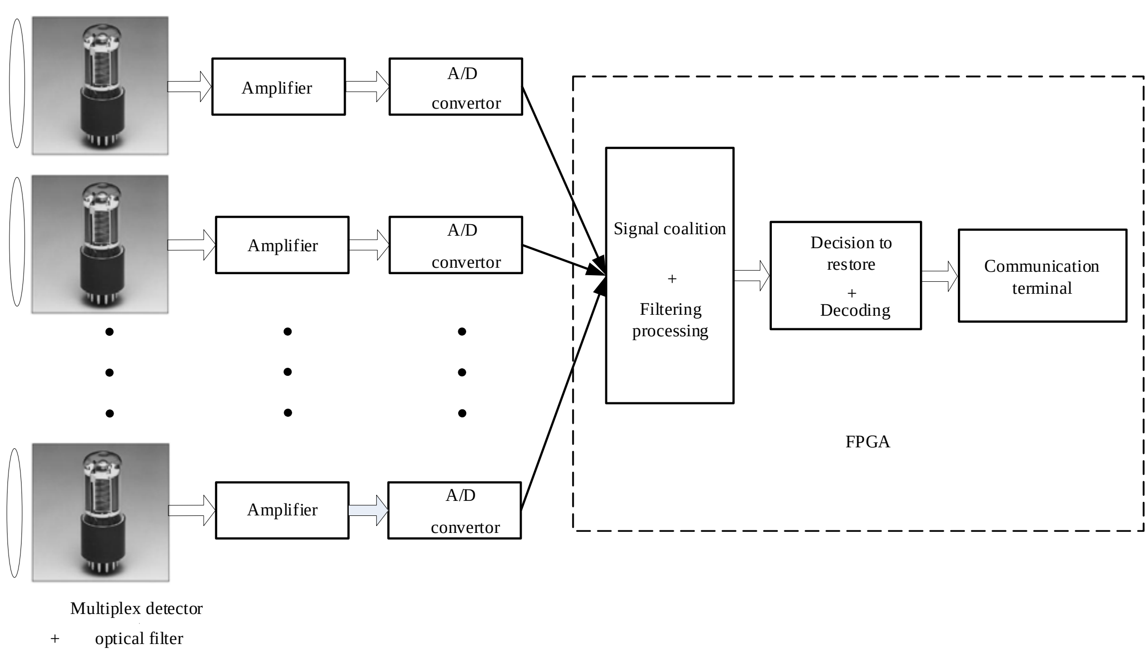

Fig. 10. Schematic diagram of multi-channel signal access scheme

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(2) Using multi-path transmission effect and referring to communication diversity mode, this paper adopts ultraviolet optical communication multi-channel access technology, which can effectively improve the receiving power and increase the communication distance. It can get a good diversity effect with the equal gain combination because that the distance of ultraviolet communication is short, the atmospheric turbulence is weak, the signal fading is not serious. Equal gain merge mode can be adopted in ultraviolet communication to reduce the complexity of the system.

(3) In intensity modulation and direct detection optical communication, the equal gain merge mode can be replaced by a single received optical antenna that has larger diameter or greater viewing angle. It can furtherly reduce system complexity. Because ultraviolet communication is "day blind" band communication, the background interference is very small. Due to the need of scattering communication, it must design a receiver with large viewing angle in order to receive more scattering light.

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