Received December 31, 2020, accepted January 19, 2021, date of publication February 23, 2021, date of current version March 23, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3061504

Atmospheric Laser Communication Technology Based on Detector Gain Factor Regulation Control

TONG WANG[1], XIN ZHAO[1], YANSONG SONG[2,4], JUNYAO WANG[3], XIAONAN YU[2], AND YIQUN ZHANG[3,4]

[1]School of Electric and Information Engineering, Changchun University of Science and Technology, Changchun 130022, China
[2]Key Laboratory of Photoelectric Measurement and Control and Optical Information Transfer Technology of Ministry of Education, Changchun University of Science and Technology, Changchun 130022, China
[3]School of Photoelectric Engineering, Changchun University of Science and Technology, Changchun 130022, China
[4]Research Center of Networks and Communications, Peng Cheng Laboratory, Shenzhen 518055, China

Corresponding author: Xin Zhao (gps.ins@163.com)

This work was supported in part by the National Natural Science Youth Foundation of China through the project "Research on Multipoint Laser Communication Method Based on Wide-Angle Beam Expander and Rotating Double Wedge" under Grant 61701045, and "Simultaneous High Speed Laser Information Transmission System between Multiple Nodes for Space Platform" under Grant 91338116, and in part by the Project "Stereoscopic Coverage Communication Network Verification Platform for China Sea" under Grant PCL2018KP002.

ABSTRACT Space laser communication, with its strong anti-jamming capability, high transmission rate and good adaptability, offers hope for the establishment of 5G mobile networks in areas that are not conducive to the erection of cables, such as islands and remote land areas. Turbulent scintillation effect is one of the important factors affecting the performance of laser communication, which can lead to the increase of communication BER and even communication interruption. Based on the working principle of the photoelectric detector in atmospheric turbulence, an optical communication receiving system based on the detector gain factor regulation control is designed, which calculates the scintillation variance according to the received signal in real time, establishes the function conversion relationship between the scintillation variance and the gain factor, realizes the closed-loop regulation control of the detector gain factor, and improves the SNR of the receiving system. A ground-based 13km static laser communication experiment was set up to test the reception performance, and the test results show that the system reduces the communication BER by more than two orders of magnitude and can be kept at 1E-6 under medium to weak turbulence (discriminated by flash variance) at a communication rate of 2.5Gbps. The technology was applied to the test of laser 5G signal transmission between the airship and the ground, and for the first time, the mobile communication (access network) signal transmission with a downlink speed of 1.230Gbps and an uplink speed of 76.4Mbps is realized, which verified the performance of mobile signal transmission between the mobile base station and the fixed station on the ground.

INDEX TERMS Space laser communications, atmospheric turbulence, 5G mobile communications, bit error rate, APD gain factor.

I. INTRODUCTION

Along with the continuous development of the information era, the continuous emergence of a large number of digital multimedia, making the communication system with fast transmission rate, large transmission capacity and wide coverage space a research hotspot. Mobile operators often use RF technology to provide high-speed network data for end users. At present, there are still situations (such as isolated islands, remote mountainous areas, etc.) where microwave antennas or optical fibers cannot be erected due to geographical, physical and bandwidth limitations. Free-space optical communication is suitable for the expansion of optical access networks and last-mile access networks due to its high transmission rate, small delay time, small size, good adaptability, and anti-jamming ability [1]–[3].

The main reason that affects the transmission performance of laser communication in atmospheric channels is atmospheric turbulence [4], [5], which leads to beam expansion, drift, and intensity fluctuation during transmission [6], [7]. Among them, intensity fluctuation is the main factor that affects the decrease of the received SNR (signal-to-noise

The associate editor coordinating the review of this manuscript and approving it for publication was Tianhua Xu.

ratio) and the increase of the BER (bit error rate). In recent years, many studies have been carried out to solve the deterioration of communication performance caused by atmospheric turbulence.

Dong-Nhat Nguyen *et al.* proposed electronic equalization to mitigate dispersion and turbulence in hybrid optical fibers and free space optical links [8]. By simulation, the equalization technique offers about an order of magnitude improvement in the BER at the received optical power of −20dBm. Abadi M M *et al.* analyzed the performance of differential detection FSO systems under weak turbulent conditions from the perspective of received signal variance [9], [10] and proposed that differential signals have better performance than single-input, single-output links. Hitam S *et al.* use differential detection to reduce the adverse effects of clouds, rain, fog, and smoke on communication under various weather conditions [11]. Djordjevic I B *et al.* proposed an adaptive modulation and adaptive coding scheme with RF feedback [12]. Under strong turbulent conditions, a variable-rate variable-power scheme or truncated channel inversion is used to mitigate turbulence-induced signal depth attenuation in. It is also proposed that modulation using adaptive LDPC coding allows communication under power saturation. Xiaoming Zhu *et al.* derive error performance bounds for free-space optical communication coding of atmospheric turbulence channels [13]. Under a weak turbulent channel (flicker variance of 0.2), it is verified by numerical analysis that the error control coding can reduce the system BER and suppress the wireless optical communication signal degradation caused by weak turbulence. Chengbin Jin *et al.* proposed an eigenmode correction method for atmospheric turbulence based on a deformation mirror to correct the wavefront distortion caused by atmospheric turbulence, and the correction performance of atmospheric turbulence was estimated using this method [14].

Methods such as differential detection and electronic equalization reduce the false detection rate of received signals, do not improve the impact of the scintillation effect on the performance of communication systems, and are only applicable to atmospheric channels with weak turbulence. Error control coding improves the error correction capability of the communication system, which is very effective in decreases BER of the communication system, but it adds a large number of redundant bits, decreases the transmission efficiency of the information, and causes a large processing delay. Adaptive optics methods are capable of correcting wavefront distortions caused by atmospheric turbulence, but the system design is complex and costly to implement. The aforementioned suppression methods improve the signal decay caused by atmospheric turbulence, but there is a lack of studies on the phenomenon of light intensity scintillation caused by turbulence leading to detector energy saturation.

The photodetector serves as the core device for photoelectric conversion at the laser communication receiving end. In an atmospheric turbulent channel, the intensity fluctuations of the optical signal can be directly reflected by the electrical signal after the photoelectric conversion of the detector [15], [16]. Haifeng Yao presents an avalanche photodiode detector (APD) based multi-level pulse amplitude modulation (M-PAM) ABER (average bit error rate) model, showing that reducing the noise of the APD by increasing its gain is an advantageous way to increase the transmission rate. It was analyzed that a larger APD gain is more significant in reducing the ABER performance under the same atmospheric turbulence conditions [17]. However, no amelioration of the atmospheric turbulence scintillation effect has been proposed.

To address the effects of turbulence on atmospheric laser communication systems, this paper proposes an optical communication receiving system based on detector gain factor regulation control. The scintillation variance of atmospheric turbulence is solved in real time according to the strength of the received signal, and the APD gain closed-loop control is realized by establishing the function conversion relationship between scintillation variance and APD gain factor, which effectively compensates for the scintillation effect on the performance of the laser communication system. In a 13-km static experiment, atmospheric turbulence scintillation variance and system mean BER were monitored at different times of the day. It is verified that the APD gain closed-loop control method can effectively mitigate the problems of light intensity decay and saturation of received light energy caused by the scintillation effect. This technology was applied in the dynamic test between airship and ground, and for the first time, a space laser communication link was used to carry the data transmission of the 5G network backbone link between the airship and the ground station, which verified the feasibility of establishing a mobile base station.

II. THEORETICAL ANALYSIS OF ATMOSPHERIC TURBULENCE

Atmospheric turbulence is a spatially and temporally dependent stochastic process that is often described using statistical quantities. Light beams pass through atmospheric turbulence with varying degrees of scattering and diffraction, resulting in random fluctuations in light intensity with time and space on the receiving plane. The ups and downs of the light intensity are usually described as a probability density function of the received light intensity, which is reflected by Rytov variance [18]. Rytov variance represents the extent to which the electric field amplitude fluctuates under atmospheric turbulence. The value depends on the structural parameters of the refractive index and horizontal distance of light propagation. The Rytov variance of the plane wave is expressed as

$$\sigma_x^2 = 0.56k^{7/6} \int_0^{L_p} C_n^2(x) \left(L_p - x\right)^{5/6} dx \tag{1}$$

where, $k = 2\pi/\lambda$ is the number of waves, C_n^2 is the atmospheric refractive index structure constant, L_p is the link distance. But it is difficult to measure Rytov variance directly in real engineering. Scintillation variance σ_I^2 is usually measured by point reception, expressed as the normalized

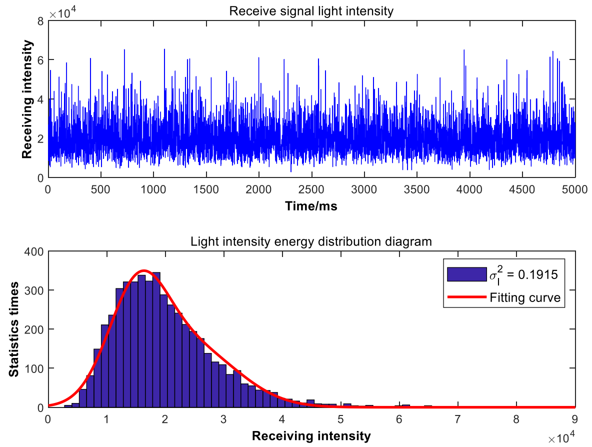


FIGURE 1. Intensity distribution of received optical signals under weak turbulence conditions.

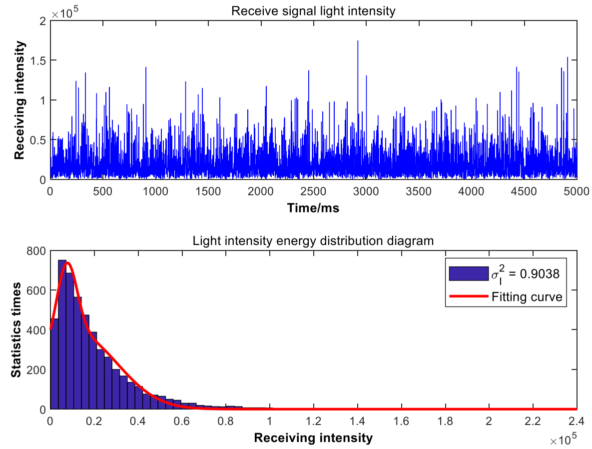


FIGURE 2. Intensity distribution of received optical signals under strong turbulence conditions.

undulating variance, which can be expressed as

$$S.I = \sigma_I^2 = \frac{\left(\langle I^2\rangle - \langle I\rangle^2\right)}{\langle I\rangle^2} \tag{2}$$

where <> is the statistical mean; I represents the intensity of light received by the detector, in cd. The initial optical signal intensity of the incident atmospheric channel at the transmitting end is assumed to be 2000cd, and the atmospheric turbulence is numerically analyzed by the Monte Carlo method. The received optical signal under different turbulence conditions of weak and strong is analyzed, and the numerical statistics of the received optical intensity are performed. The simulation results are shown in Figure 1 and Figure 2.

The curves were fitted according to the light intensity distribution at the receiving end, and the fitted curves conformed to the results of a logarithmic statistical distribution. The received light intensity under weak turbulent conditions is concentrated in the range of 15000-25000 cd, and although there are energy fluctuations, there is no significant signal decay. As the variance of flicker increases, the trailing edge of the received light intensity distribution in the infinity direction becomes more obvious, indicating that the signal intensity fluctuates more sharply when the channel inhomogeneity increases. Under strong turbulence conditions, the distribution of the received signal strengths gradually approaches the zero regions, and the received signal is smaller than the threshold value set by the detector resulting in a misjudgment "0".

In summary, the received light intensity fluctuates due to atmospheric turbulent scintillation, resulting in changes in the received power of the detector. When the received signal is less than the detector threshold, the detector will not respond, when the received signal is too large, the detector will be saturated, and the detector will break down in severe cases. The amplification is adjusted as a whole by means of an external direct multi-stage amplification circuit. This method has the advantage of fixed detector sensitivity, reliable operation, and the ability to vary the threshold, but does not improve the SNR of the receiving system. If the response threshold is increased and the SNR is improved by appropriately sacrificing detector sensitivity within the range allowed by the communication, it will be possible to mitigate the effects of turbulent scintillation on the laser communication receiving system and improve the performance of the communication system to a certain extent.

III. DETECTION-RECEPTION METHOD FOR APD GAIN FACTOR REGULATION CONTROL

A. DETECTION OF RECEIVING SYSTEMS IN FSO

Intensity modulation/direct detection (IM/DD) is commonly used in free-space optical communication systems, and if the receiving alignment problem in the communication system is not considered, it is assumed that the communication system is only affected by atmospheric channel turbulence, as shown in Figure 3 for the IM/DD communication system model.

The IM/DD communication model can be structurally divided into two parts: the transmitting end and the receiving end. The data to be transmitted at the transmitting end is modulated and loaded on the laser, then shaped by the optical antenna and emitted as parallel light. Through the atmospheric channel to the receiving end, the optical antenna will converge the signal light on the APD target surface to complete the conversion from optical signal to electrical signal, and realize the recovery of clock and data through amplification, filtering and demodulation.

As a sensitive component at the receiving end, the APD's operating performance directly determines the performance of the entire communication system. The APD is a detector that operates under reverse voltage and uses the avalanche multiplication effect to amplify the photocurrent, and the effective value of the photocurrent after multiplication can be expressed as [19]

$$i_p = \frac{e\eta P_{opt} M}{\sqrt{2}hv} \tag{3}$$

where, e is the electron dielectric constant, η is the quantum efficiency, M is the gain factor, $h = 6.624 \times 10^{-34} W \cdot s/Hz$

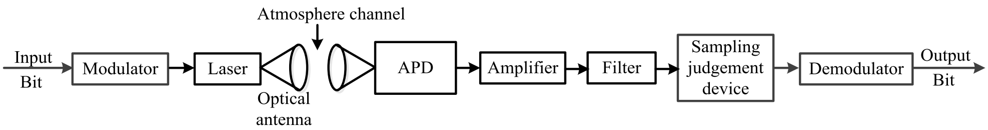


FIGURE 3. IM/DD communication system model.

is Planck's constant, $v = \lambda/c$ is the optical frequency, P_{opt} is the average received optical power. Assuming that the incident signal optical field is $E_S(t) = I\cos\omega t$, where I represents the signal optical intensity and ω is the signal optical frequency, the average optical power as

$$P_{opt} = \overline{E_S^2(t)} = I^2 \tag{4}$$

The noise of APD mainly includes optical noise and electrical noise. The optical noise is generated by the background radiation and signal radiation, and the electrical noise is composed of thermal noise and scattering noise, which is an important parameter to limit the performance of APD. The scattering noise can be expressed as

$$\left[i_S^2\right] = 2e\left(I_P + I_B + I_D\right)M^2F(M)B \tag{5}$$

where, I_p for photocurrent, I_B is the DC current generated by background radiation and I_D is dark current. B is the equivalent bandwidth. $F(M) = k_AM + (1-k_A)\left(1-1/M\right)$ is the excess noise factor, where $k_A \approx 0.5$.

The thermal noise mean square current can be expressed as

$$\left[i_T^2\right] = \frac{4kTB}{R_{eq}} \tag{6}$$

where k is the Boltzmann constant, T is the operating temperature, and Req is the APD equivalent resistance.

In optoelectronic conversion at the receiving end, the most critical performance indicator is the SNR of the system, which determines the communication performance of the system. According to Eq. 3 - Eq. 6, the SNR of the APD received signal is expressed as

$$SNR = \frac{S}{N} = \frac{\left(\frac{e\eta A_{rec}I}{hv}\right)^2}{4e\left(I_P + I_B + I_D\right)F(M)B + \frac{8kTB}{R_{eq}M^2}} \tag{7}$$

From the above equation, the molecules increase with increasing input optical power. If the input optical power is certain, with the increase of the gain factor M, the first term of the denominator gradually increases, and the second term decreases with the increase of M. Under the premise of sacrificing detection sensitivity, proper adjustment of the APD gain factor M can improve the system SNR and meet the overall technical specifications. The input optical power for a period of time according to the formula (2) directly reflects the atmospheric turbulence scintillation variance, from which can be established a function between the scintillation variance σ_I^2 and M, according to this function to

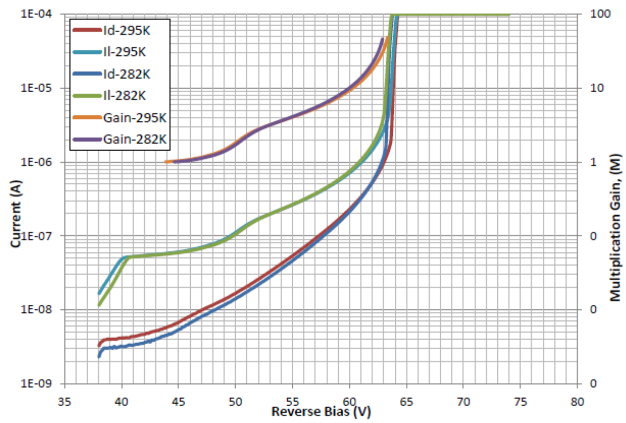


FIGURE 4. APD gain characteristic curve.

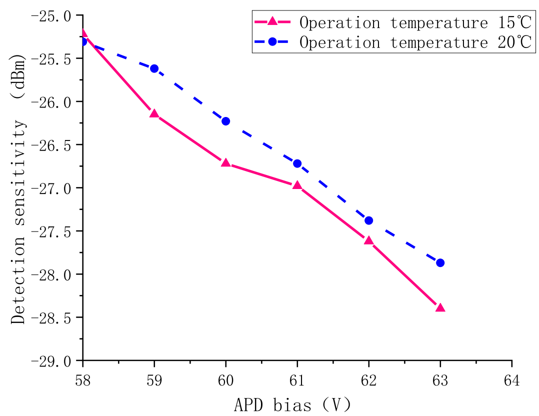


FIGURE 5. Detection sensitivity curves of APD at different biases.

achieve a closed-loop regulation control, improve SNR and performance of communication systems.

Voxtel Siletz BSI RIP1-JJRC series avalanche photodiodes were used in the experiment, and their photocurrent gain characteristic curves are shown in Figure. The horizontal axis is the reverse bias voltage VAPD loaded on the cathode of the avalanche photodiode, the left side of the vertical axis is the output photocurrent IAPD, and the right side is the APD multiplication gain coefficient M. Figure. 4 shows the multiplication gain factor M increases with the inverse bias voltage, causing the APD photocurrent to increase exponentially and rapidly. When the inverse bias voltage exceeds 63V, the APD gain rises sharply and produces avalanche breakdown at about 64V, in order to ensure system safety and reliability, the maximum bias limit value is set to 63V. The APD gain factor M corresponds approximately to the inverse

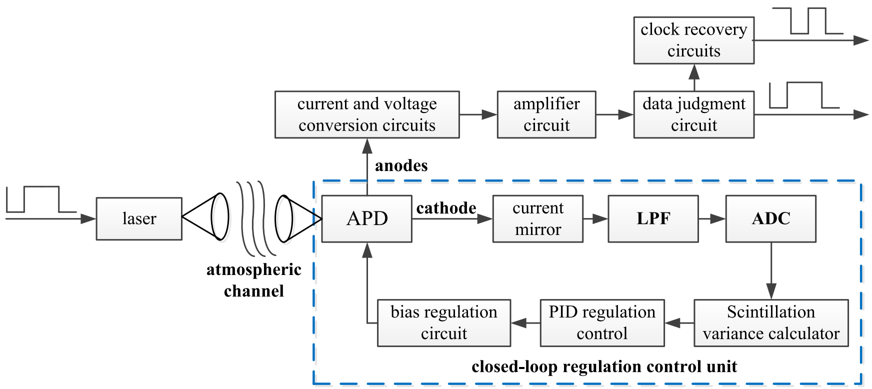


FIGURE 6. Schematic diagram of APD gain closed-loop regulation control method system.

bias voltage VAPD as follows.

$$M \approx (5.87E - 9) \exp (0.29 V_{APD}) \tag{8}$$

To further analyze the effect of multiplication gain factor M on the APD SNR, the APD detection sensitivity (also known as noise equivalent power, which refers to the power of the input signal required when the signal output is equal to the noise output) was measured at 58-63 V bias (communication rate of 2.5 Gbps) when the BER satisfies 1E-7. The measurement results are shown in Fig. 5. Under the same conditions, the increase of the gain factor M helps to improve the detection sensitivity of the APD and achieve the purpose of improving the SNR of the communication system. Therefore, this characteristic of APD can be used to improve the suppression of atmospheric turbulence scintillation effect at the receiving end of the laser communication system.

B. APD GAIN FACTOR REGULATION CONTROL METHOD

To improve the fluctuation of the received light intensity due to atmospheric turbulence, the atmospheric light intensity scintillation variance is calculated in real time based on the APD photocurrent value at the receiving end. According to the function conversion relationship between the flicker variance and the gain factor, the closed-loop regulation control of the APD's gain factor is achieved using PID (Packet Identifier) control. The stable APD output signal is obtained to improve the SNR of the system, compensate for the effect of light intensity flicker on the BER of the communication system, although this method occasionally reduces the detection sensitivity of the APD. The APD receiving system consists of a closed-loop regulation control unit and a data demodulation unit, the system principle is shown in Figure 6.

The classical APD receiver circuit connects the anode of the APD with a transimpedance amplifier, converts the received signal from current to voltage, and demodulates the data signal through amplification, judgment, clock data recovery and other circuits. The closed-loop regulation control system of the APD gain factor is built on the cathode of the APD, improving on the classical receiver circuit.

A current mirror is connected to the cathode of the APD to extract the mirror image of the photogenic current of the APD, and the output value is IAPD. After low-pass filter shaping to eliminate the influence of modulation information, the average photocurrent value, the amplification, analog-to-digital conversion (ADC) to achieve the acquisition of photovoltaic power. The atmospheric Greenwood frequency is 1 to 100 Hz, thus setting the sampling frequency to 1 kHz. The collected current value is used to calculate the atmospheric turbulence scintillation variance in real time according to Eq. (2), and the error amount is obtained by comparing the scintillation variance with the threshold current ISET (which is related to inherent factors such as communication distance, background noise, emitted optical power, etc.) set in the turbulence-free channel. This error amount is generated by the PID control algorithm according to Eq. (8). The APD gain factor M is adjusted according to the size of the turbulence in real time to achieve closed-loop control of the APD gain factor and effectively compensate for the effects of turbulence scintillation on the communication system. Although changing the gain factor M will occasionally sacrifice the detection sensitivity of the APD detector to meet the overall specification design requirements.

IV. STATIC SPACE OPTICAL COMMUNICATION EXPERIMENT

In order to verify the improvement of the performance of the communication receiving system by adding APD gain closed-loop control, a long-range static communication test was conducted between the Science and Technology Building of Changchun University of Science and Technology and the building in Jingyuetan park. The experimental site is shown in Figure 7 with a communication distance of about 13km.

Link budget for space optical communication at a communication distance of 13 km, assuming a transmit power of 20 dBm. The optical loss at the transmitting end is due to factors such as the transmitting optical lens transmittance, and if the transmittance is 60%, the optical loss at the transmitting end is -2.2 dBm. The spatial loss is the geometric loss of the laser signal, which is the ratio of the area of the light spot

FIGURE 7. Map of the optical propagation path.

TABLE 1. 13km link power budget.

Emitting optical power	2 dBm
EDFA output signal power	20 dBm
Emission optical loss	-2.2 dB
Space loss	-24.6 dB
Atmospheric losses （V=8km）	-8 dB
Follow the aim mismatch loss	-1 dB
Receive optical loss	-4.4 dB
Receiving end signal detection power	-20.2 dBm

transmitted by the actual receiving aperture to the area of the light spot reaching the receiving surface. Atmospheric loss can be approximated by atmospheric visibility V(km) with the attenuation coefficient expression [15] as follows.

$$\sigma = \frac{3.91}{V}\left[\frac{\lambda}{550}\right]^{-q} \tag{9}$$

$$q = \begin{cases} 1.6 & (V > 50) \\ 1.3 & (6 < V < 50) \\ 0.16 & V + 0.34\,(1 < V < 6) \\ V - 0.5 & (0.5 < V < 1) \end{cases} \tag{10}$$

Following aim mismatch loss is the loss of optical energy due to optical tracking aiming deviations. The optical loss at the receiving end includes the loss of the optical lens transmittance and the coupling loss of the spatially optically coupled fiber, if both transmittances are 60%. Then the 13km link power budget is shown in Table 1.

Build an experimental system as shown in Figure 8, emitting optical power of 20dBm. According to the APD photocurrent measurement method described in Section 3.2, the photocurrent of the APD under closed-loop regulation control and uncontrolled conditions is monitored to obtain the light intensity scintillation variance of atmospheric turbulence at this moment (11 a.m.) by probability distribution statistics. The results are shown in Fig. 9, Fig. 9(a) and (b) show the statistical results of the probability density of received photocurrent values and received current values of the APD without control, and Fig. 9(c) and (d) show the statistical results of the probability of received current values and received current values of the APD after increasing the closed-loop control.

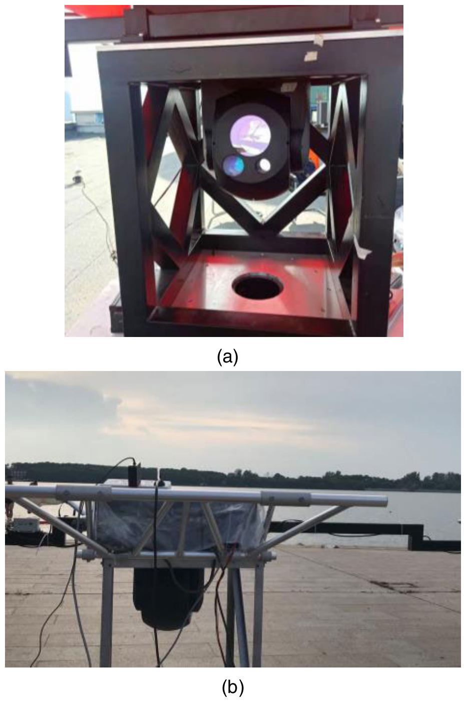


FIGURE 8. 13Km static space optical communication test field diagram. (a) Optical transceiver A. (b) Optical transceiver B.

When uncontrolled, the probability density of the APD receiving photocurrent exhibits a negative exponential

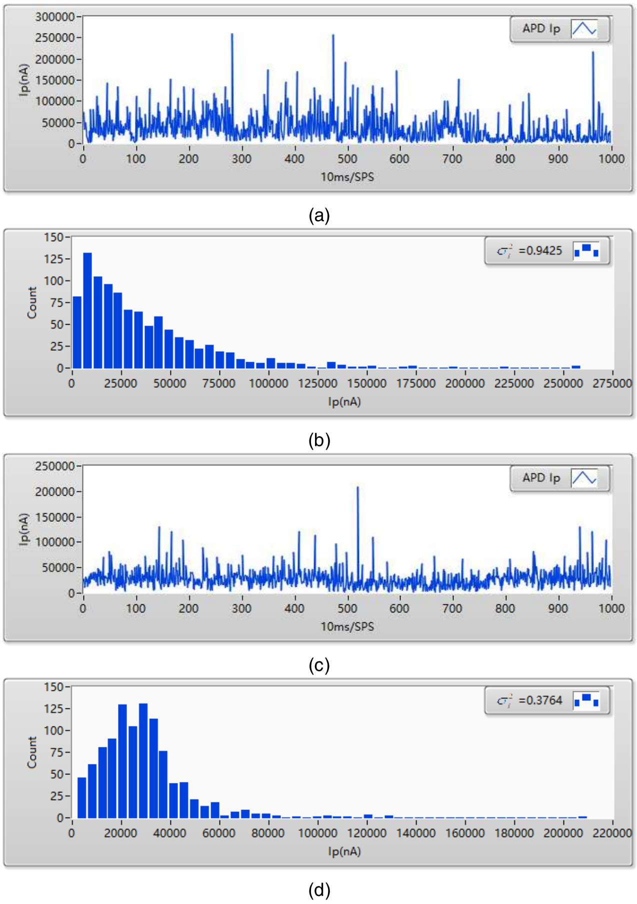


FIGURE 9. Measurements result of light intensity scintillation variance for 13 km atmospheric turbulence. (a) without control of APD photocurrent value. (b) Probability density statistics of received energy without control. (c) Closed-loop regulation control of APD photocurrent value. (d) Probabilistic density statistics of received energy for closed-loop regulation control.

distribution. The trailing is more pronounced in the infinity direction, with large fluctuations in the received signal energy and an atmospheric turbulence light intensity scintillation variance of 0.9425. With the addition of closed-loop regulation at the receiving end of the laser communication, the peak of the light energy received by the APD is shifted to the right, and the energy is concentrated in the range of 18,000nA to 32,000nA, with an atmospheric turbulence variance of 0.3764. Testing the communication BER under these conditions, as shown in Figure 10, the average BER is 6.29E-4 when uncontrolled and 9.29E-6 after closed-loop regulation control, which reduces the BER by two orders of magnitude.

The experimental results show that the APD gain closed-loop control method can effectively reduce the system BER and improve the communication quality.

To further verify the effect of closed-loop control of APD gain on the improved performance of the detection-reception system, the atmospheric turbulence light intensity scintillation coefficient and the communication system BER are measured at different times of the day. Repeating the above experimental procedure, the APD photocurrent values were

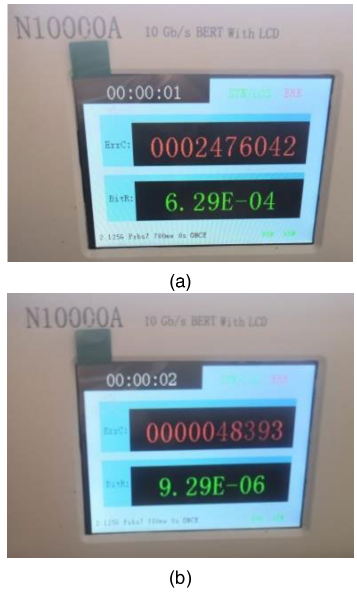


FIGURE 10. 13km communication experiment BER test chart. (a) Uncontrolled. (b) Closed-loop regulation control.

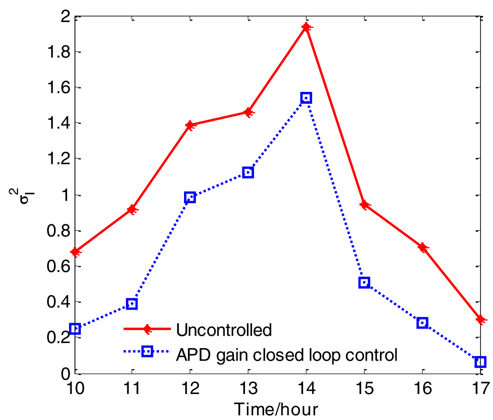


FIGURE 11. Atmospheric scintillation variance statistics at different time periods.

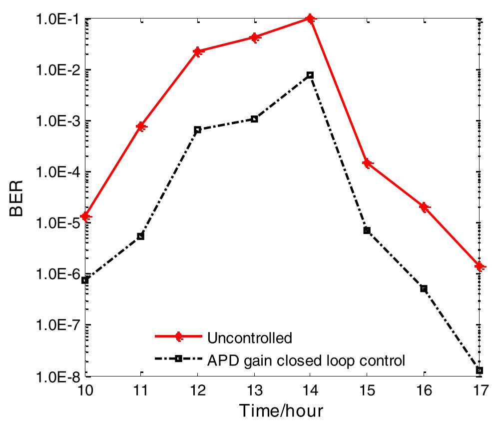


FIGURE 12. BER test results at different time periods.

collected at different times of the day, and the atmospheric light intensity flicker variance at different times of the day was obtained by the light intensity energy distribution

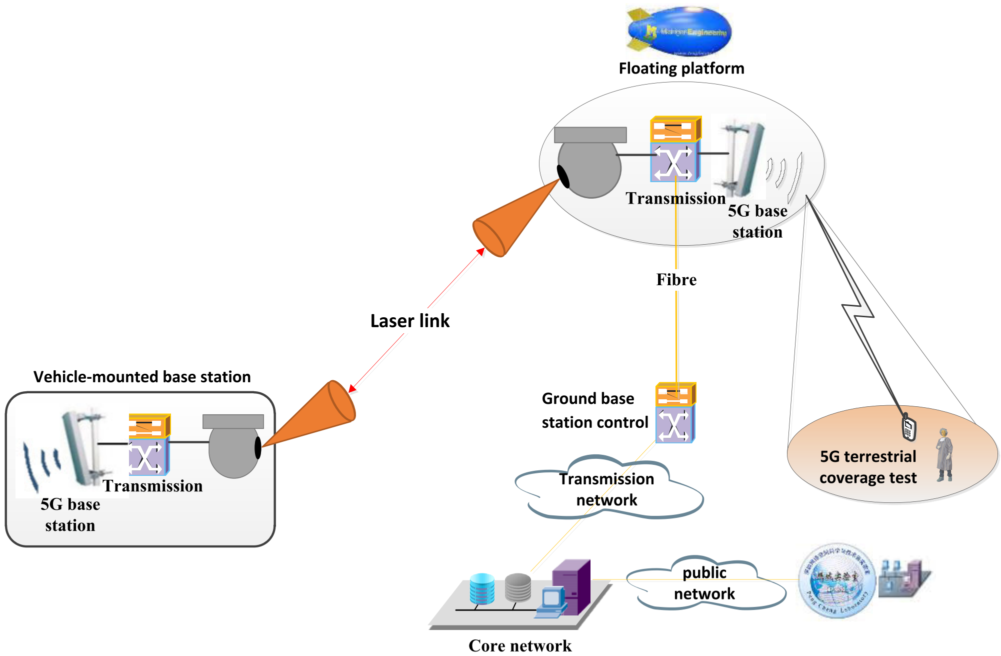


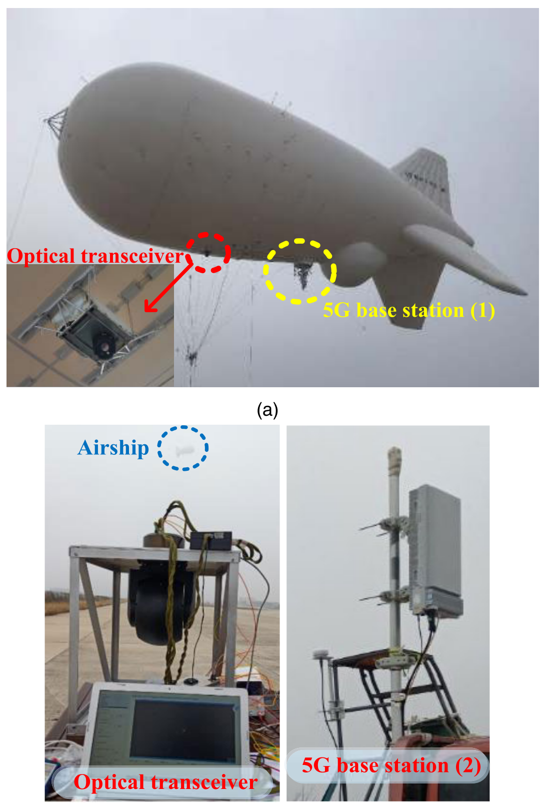
FIGURE 13. Experimental block diagram of laser communication and 5G network data transmission.

statistics, the results are shown in Figure 11. The BERs for different time periods measured by the BER meter are shown in Figure 12.

The results are shown in Figure 11, where the scintillation variance is greatest at 14:00, the strong decay of atmospheric turbulence is more pronounced, which manifests as strong turbulence, and the average BER at uncontrolled moments is 1.09E-1 orders of magnitude, which is reduced by one order of magnitude after closed-loop regulation. After 16:00 the scintillation variance is smaller and the light intensity scintillation is weaker, showing weak turbulence. The average BER is 2.01E-5 orders of magnitude when uncontrolled, and is optimized to 5.10E-7 after closed-loop control. The experimental results show that the APD gain closed-loop regulation control method significantly improves the energy decay of medium and weak turbulence, improves the SNR of the receiving system, reduces the average BER of the communication system, and increases the reliability of the laser communication performance under the atmospheric turbulence channel.

V. LASER COMMUNICATION AND 5G NETWORK DATA TRANSMISSION EXPERIMENTS

A demonstration experiment of dynamic laser communication between a floating platform (airship) and a ground base station was conducted in Jingmen City, Hubei Province. The test communication distance is about 800 meters, and the space laser communication equipment and 5G base station equipment are carried on the floating platform to build an air base station, and the chain network is formed by the air-ground laser link and the 5G base station on board. The air base station is connected to the ground console via optical fiber. The ground console is connected to the core and public networks and uses 5G terminal equipment to test the transmission rate of the chain network, as shown in Figure 13.



(a)

(b)

FIGURE 14. Experimental field diagram of laser communication and 5G network data transmission.

FIGURE 15. **5G terminal equipment uplink and downlink rate test chart.**

The test site is shown in Figure 14. By aiming, capturing and tracking makes the laser communication link alignment complete, the atmospheric scintillation variance is 0.2215 in uncontrolled testing, and the scintillation variance is 0.0408 at the receiving end after closed-loop regulation control of APD gain factor, and the ABER is 6.47E-7 at 2.5Gbps communication rate. At the same time, the data transmission rate of the chain network consisting of the laser communication system and the 5G network is tested, and the network transmission rate is tested through the 5G terminal, and the measurement results are shown in Figure 15.

The results show that the downlink communication rate tested through the 5G terminal all exceeded 1.2Gbps and the uplink rate was 76.4Mbps (the uplink was only used for TCP protocol transmission, no data upload, so the rate was low). The effective service range of an airborne base station at an altitude of 300 m is 6 km and the signal coverage is more than 10 km. The transmission of 5G network signals over space optical communication links improves the transmission efficiency and anti-jamming performance of air base stations. The success of this experiment provides a technology sample for the efficient coverage of 5G networks over large areas such as oceans and remote lands.

VI. CONCLUSION

The construction of 5G mobile communications has become an inevitable trend in the development of high-speed information networks, and the realization of mobile networks in remote areas such as islands is the focus of integrated network construction. Free space communication is the main way to address environmental interference and high-speed data transmission requirements. By studying the effect of atmospheric turbulence on the laser communication system, the communication reception method based on the detection of APD gain factor closed-loop regulation control is proposed. The static 13km communication experiments verify that the APD gain closed-loop control method has a significant improvement in system performance and reduces the average BER of the system by two orders of magnitude under a strong decaying channel with medium and weak turbulence. In the demonstration test of the dynamic laser communication system, the first space mobile communication network demonstration and validation platform was successfully built, using space laser communication as the backbone link to transmit 5G network signals, achieving a downlink speed of 1.2Gbps 5G mobile network data transmission. It has promoted the development of terrestrial public mobile communication networks to space and wide areas, laying a solid foundation for the realization of dynamic space networking.

REFERENCES

[1] M. Elamassie and M. Uysal, "Incremental diversity order for characterization of FSO communication systems over lognormal fading channels," *IEEE Commun. Lett.*, vol. 24, no. 4, pp. 825–829, Apr. 2020, doi: 10.1109/LCOMM.2020.2966479.

[2] M. A. Amirabadi and V. T. Vakili, "Deep learning for channel estimation in FSO communication system," *Opt. Commun.*, vol. 459, no. 9, Mar. 2019, Art. no. 124989, doi: 10.1016/j.optcom.2019.124989.

[3] N. A. M. Nor, Z. F. Ghassemlooy, J. Bohata, P. Saxena, M. Komanec, S. Zvanovec, M. R. Bhatnagar, MA. Khalighi, "Experimental investigation of all-optical relay-assisted 10 Gb/s FSO link over the atmospheric turbulence channel," *J. Lightw. Technol.*, vol. 35, no. 1, pp. 45–53, Jan. 1, 2017, doi: 10.1109/JLT.2016.2629081.

[4] M. Toyoshima, H. Takenaka, and Y. Takayama, "Atmospheric turbulence-induced fading channel model for space-to-ground laser communications links," *Opt. Exp.*, vol. 19, no. 17, pp. 15965–15975, Aug. 2011, doi: 10.1364/OE.19.015965.

[5] Y. Li, C. Gao, M. S. Leeson, and X. Li, "Asymptotic analysis of V-BLAST MIMO for coherent optical wireless communications in Gamma-Gamma turbulence," *Opt. Exp.*, vol. 26, no. 21, pp. 27931–27944, Oct. 2018, doi: 10.1364/OE.26.027931.

[6] M. Ijaz, Z. Ghassemlooy, J. Perez, V. Brazda, and O. Fiser, "Enhancing the atmospheric visibility and fog attenuation using a controlled FSO channel," *IEEE Photon. Technol. Lett.*, vol. 25, no. 13, pp. 1262–1265, Jul. 2013, doi: 10.1109/LPT.2013.2264046.

[7] C. Chen and H. Yang, "Characterizing the statistical distribution for transmission coefficient of turbulent optical orbital-angular-momentum channels," *Opt. Exp.*, vol. 27, no. 20, pp. 28968–28982, Sep. 2019, doi: 10.1364/OE.27.028968.

[8] DN. Nguyen, S. Zvanovec, Z. Ghassemlooy, "Mitigation of dispersion and turbulence in a hybrid optical fibre and free-space optics link using electronic equalisation," *Optik*, vol. 196, Nov. 2019, Art. no. 163154, doi: 10.1016/j.ijleo.2019.163154.

[9] M. Mansour Abadi, Z. Ghassemlooy, M.-A. Khalighi, S. Zvanovec, and M. R. Bhatnagar, "FSO detection using differential signaling in outdoor correlated-channels condition," *IEEE Photon. Technol. Lett.*, vol. 28, no. 1, pp. 55–58, Jan. 1, 2016, doi: 10.1109/LPT.2015.2480011.

[10] M. M. Abadi, Z. Ghassemlooy, S. Zvanovec, M. R. Bhatnagar, M. A. Khalighi, Y. Wu, "Impact of link parameters and channel correlation on the performance of FSO systems with the differential signaling technique," *J. Opt. Commun. Netw.*, vol. 9, no. 11, pp. 138–148, Nov. 2017, doi: 10.1364/JOCN.9.001062.

[11] S. Hitam, M. K. Abdullah, M. A. Mahdi, H. Harun, A. Sali, and M. Fauzi, "Impact of increasing threshold level on higher bit rate in free space optical communications," *J. Opt. Fiber Commun. Res.*, vol. 6, nos. 1–6, pp. 22–34, Aug. 2009, doi: 10.1007/s10297-009-9004-6.

[12] I. B. Djordjevic, "Adaptive modulation and coding for free-space optical channels," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 2, no. 5, pp. 221–229, May 2010, doi: 10.1364/JOCN.2.000221.

[13] X. Zhu and J. M. Kahn, "Performance bounds for coded free-space optical communications through atmospheric turbulence channels," *IEEE Trans. Commun.*, vol. 51, no. 8, pp. 1233–1239, Aug. 2003, doi: 10.1109/TCOMM.2003.815052.

[14] C. Jin, X. Zhang, W. Sun, N. Li, Q. Mu, Z. Cao, Y. Wang, and L. Xuan, "Correction performance estimation of atmospheric turbulence based on eigenmode method," *Opt. Commun.*, vol. 466, Jul. 2020, Art. no. 125661, doi: 10.1016/j.optcom.2020.125661.
[15] P. Saxena, A. Mathur, M. R. Bhatnagar, and Z. Ghassemlooy, "BER of an optically pre-amplified FSO system under Málaga turbulence, pointing errors, and ASE noise," in *Proc. IEEE 28th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Oct. 2017, pp. 1–6.
[16] H. Yao, C. Chen, X. Ni, S. Tong, and H. Jiang, "Analysis and evaluation of the performance between reciprocity and time delay in the atmospheric turbulence channel," *Opt. Exp.*, vol. 27, no. 18, pp. 25000–25011, Sep. 2019, doi: 10.1364/OE.27.025000.
[17] H. Yao, X. Ni, C. Chen, B. Li, X. Zhang, Y. Liu, S. Tong, Z. Liu, and H. Jiang, "Performance of M-PAM FSO communication systems in atmospheric turbulence based on APD detector," *Opt. Exp.*, vol. 26, no. 18, pp. 23819–23830, Sep. 2018, doi: 10.1364/OE.26.023819.
[18] H. E. Nistazakis, T. A. Tsiftsis, and G. S. Tombras, "Performance analysis of free-space optical communication systems over atmospheric turbulence channels," *IET Commun.*, vol. 3, no. 8, pp. 1402–1409, Jul. 2009, doi: 10.1049/iet-com.2008.0212.
[19] S. Khankalantary, M. T. Dabiri, and H. Safi, "BER performance analysis of drone-assisted optical wireless systems with APD receiver," *Opt. Commun.*, vol. 463, May 2020, Art. no. 125309, doi: 10.1016/j.optcom.2020.125309.

TONG WANG received the M.Eng. degree from the School of Information and Communication Engineering, Changchun University of Science and Technology, Changchun, China, in 2019, where she is currently pursuing the Ph.D. degree. Her research interests include atmospheric laser communication and design of optical systems.

XIN ZHAO received the B.Sc. and M.Sc. degrees and the Ph.D. degree in scientific instruments from the Changchun University of Science and Technology, in 2002, 2005, and 2011, respectively. His research interests include space laser communication and opto-electronic measuring technology.

YANSONG SONG received the B.Sc. and M.Sc. degrees from the Changchun University of Science and Technology, in 2006 and 2009, respectively, where he is currently pursuing the Ph.D. degree. His research interest includes space laser communication.

JUNYAO WANG received the M.Eng. degree from the School of Optoelectronic Engineering Technology, Changchun University of Science and Technology, Changchun, China, in 2020, where he is currently pursuing the Ph.D. degree. His research interests include atmospheric laser communication and design of optical systems.

XIAONAN YU received the Ph.D. degree in optoelectronic engineering from the Changchun University of Science and Technology, China, in 2018. Since 2012, he has been participating in laser communication and ranging technology development with the National and Local Joint Engineering Research Center of Space Optoelectronics Technology, where he is currently the Supervisor of the Signal Processing Group, which performs research in optical communications, laser ranging, laser detection, and synchronization.

YIQUN ZHANG received the M.Eng. degree from the School of Optoelectronic Engineering Technology, Changchun University of Science and Technology, Changchun, China, in 2019, where he is currently pursuing the Ph.D. degree. He is working with the Research Center of Networks and Communications, Peng Cheng Laboratory. His research interest includes design of optical communication systems.