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Influence of Soot Aerosol on Satellite-ground Quantum Communication Performance

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Abstract

Soot aerosol is an important part of atmospheric aerosol, which has important influence on the propagation of quantum signal. In order to study the influence of soot aerosol on satellite-ground quantum communication, according to the size distribution parameter and extinction coefficient of the soot aerosol, the influence of the concentration of the soot aerosol particles and the transmission distance on the attenuation of the link is analyzed. The simulation experiments of channel capacity, channel fidelity and channel bit error rate (Ber) are carried out with amplitude-damped channel. The simulation results show that the soot aerosol concentration increases from $2.1\times10^6\,/\,\mathrm{m}^3$ to $3.2\times10^6\,/\,\mathrm{m}^3$, the link attenuation factor increases from $0.3\mathrm{dB}\,/\,\mathrm{km}$ to $0.46\mathrm{dB}\,/\,\mathrm{km}$, the fidelity decreases from 0.98 to 0.97, and the bit error rate increases from 0.0087 to 0.0122 at a transmission distance of $3\mathrm{km}$. When the transmission distance is $6\mathrm{km}$ and the particle concentration is $2.1\times10^6\,/\,\mathrm{m}^3$, $2.7\times10^6\,/\,\mathrm{m}^3$ and $3.9\times10^6\,/\,\mathrm{m}^3$, the channel capacity increases from 1.078 to 1.0809, and then decreases to 1.0804. Therefore, the soot aerosol has influence on the performance of satellite-ground quantum communication, and the degree of influence is different. In order to ensure the reliability of quantum communication between satellite and ground, the parameters can be adjusted to ensure the normal transmission of quantum signal.

Keywords quantum communication; soot aerosol; link attenuation; amplitude damping channel; channel capacity; channel fidelity

I. INTRODUCTION

Quantum communication is a new type of communication method which uses quantum superposition state and entanglement effect to transmit information. It has absolute security guarantee which can not be broken by eavesdropping and computation. It is mainly divided into quantum teleportation and quantum cryptography. Quantum cryptography, also known as quantum cryptography, uses measurements of the quantum superposition state to achieve secure quantum key sharing between the two sides of the communication, and through a one time symmetric encryption system to achieve unconditional absolute security communication. Quantum secure communication based on quantum cryptography has become a potential technology to ensure the security of network information in the future, and it is a hotspot in the field of quantum communication theory and application research [1].

The first quantum cryptography communication scheme was proposed(1984), the famous BB84 scheme, and the first experimental principle of quantum key distribution was demonstrated [2]. The issue of Physical Review Letters, the leading International Journal of Physics, published a research paper entitled 13 km free space entangled photon distribution: towards global quantum communications based on artificial satellites(Jianwei Pan et al. 2005), it has been proved for the first time in the world that the properties of entanglement can be maintained and can be used in efficient and safe quantum communication after the entangled photon penetrates the ground atmosphere equivalent to the entire thickness of the atmosphere [3]. The strategic report on Quantum Information Processing and communication was published(2008), which proposed a phased development goal for quantum communication in Europe, including the realization of the ground quantum communication network, satellite-ground quantum communication, space-ground integrated quantum communication network, and so on [2].

Light quantum signal is transmitted by quantum teleportation, which is based on the theory of quantum entangled state. Compared with classical communication, quantum communication has more advantages in security and efficiency. In the process of quantum communication, all kinds of substances in the atmosphere will cause scattering and extinction of light. The extinction characteristics of marine aerosol in free space are studied in reference [4], which provides a basis for studying the distribution function of soot aerosol. The transmission characteristics of soot aerosol in the medium were studied in reference [5], which provided a basis for studying the scattering characteristics of soot aerosol. The light scattering and transmission characteristics of soot and haze aerosol were studied in literature [6], which provided a basis for studying the particle concentration of soot aerosol. The influence of snowstorm on the quantum communication channel in free space is studied in literature [7], which provides a theoretical basis for adjusting the parameters of quantum communication system in snowstorm. At present, the domestic and foreign scholars have little research on the changes of quantum communication performance under the soot aerosol background.

Soot aerosol is one of the important components of atmospheric aerosol, which is formed by the emission of particulate matter from biomass combustion. The contribution of biomass combustion to urban air pollution is increasing year by year. Based on the statistical analysis of the changes in the atmospheric routine monitoring indicators and other data in Shanghai over the past 10 years, the following three facts have been discovered: first, the annual average visibility of the atmosphere in Shanghai is 10 km lower, and the whole atmosphere is in the level of haze, second, the probability of acid rain continued to rise and precipitation pH continued to decline, the third is the concentration of fine particles continued to rise [8]. Deng Congrui found that due to the high hygroscopicity of sulfate, nitrate and ammonium salt, the emission from biomass combustion can greatly change the atmospheric optical properties and cause serious soot and dust in the region [8].

Based on the basic theory of electromagnetic scattering, Huang Chaojun has carried out the research on the light scattering and transmission characteristics of condensed particles of soot and haze aerosol by using the numerical calculation method of electromagnetic scattering, a single-particle-size and multi-particle-size model of agglomerated particles of soot and haze was established to solve the problem of light scattering of agglomerated particles of aerosol [6]. Therefore, it is of great significance to analyze the extinction characteristics of soot particles in different concentrations and their effects on quantum communication in free space.

According to the size distribution parameters of soot aerosol particles, the extinction coefficient of soot aerosol is obtained, and the relationship between the attenuation of the chain and the concentration of soot aerosol particles and the transmission distance is analyzed by simulation. For the amplitude-damped channel, the channel capacity, the channel fidelity and the channel bit error rate (Ber) are simulated, and the relationship between the three factors and the soot aerosol particles and the transmission distance is studied, it lays a foundation for the normal transmission of optical quantum communication signal under the influence of soot aerosol.

II. INFLUENCE OF SOOT AEROSOL ON LINK ATTENUATION

The properties of aerosol particles are related to the shape, composition and size of the particles. The size parameter of soot aerosol can be expressed as:

$$x = 2\pi R / \lambda \tag{1}$$

Where, x is the size parameter to parameterize the probability distribution of the particles, R is the radius of the aerosol particles, in $\mu\mathrm{m}$, λ is the wavelength of the incident light, in $\mu\mathrm{m}$.

The scattering process can be divided into three types according to the size of the scale parameters, which are Rayleigh scattering, Mie scattering and geometrical optical scattering. The Mie scattering is used to calculate the extinction characteristic of soot aerosol, because the size parameter x is between $0.1 \sim 50.0$ [9], which accords with the Mie scattering condition.

At present, the aerosol particle size distribution parameters generally use the widely applicable log-normal distribution function [10], its expression is:

$$n(R)=\frac{dN}{dR}=\frac{n_0}{\sqrt{2\pi}\ln 10\cdot R\ln\sigma_{gm}}\cdot\exp\left[-\frac{\left(\ln R-\ln R_{gm}\right)^2}{2\ln^2\sigma_{gm}}\right] \tag{2}$$

Where, n_0 is the concentration of the number of particles in the soot aerosol, R_{gm} is the average radius of the particles, in $\mu\mathrm{m}$, and σ_{gm} is the Geometric standard deviation. Table 1 gives the typical scale parameters of several common aerosol [11].

Table 1 Typical size parameters of common aerosols

Parameter	Oceanic	Dust-like	Soot	Water-soluble
$R_{gm}/\mu m$	0.3000	0.5000	0.0118	0.0500
σ_{gm}	2.5100	2.9900	2.0000	2.9900

The visible light can be absorbed and scattered by the soot aerosol particles in the process of atmospheric transmission, and the energy attenuation carried by the particles is inevitable. Therefore, it is very important to study the extinction characteristics of aerosol particles in visible light. The extinction coefficient [12] of soot aerosol particles can be expressed as:

$$k_{ext}=\pi\int_{R_1}^{R_2}Q_{ext}\left(m,R,\lambda\right)n\left(R\right)R^2dR \tag{3}$$

Where, R_1 and R_2 are the lower limit and upper limit of the radius, m is the complex refractive index and $Q_{ext}\left(m,R,\lambda\right)$ is the extinction efficiency factor [13], which can be expressed as:

$$Q_{ext}=\frac{2}{x^2}\sum_{n=1}^{\infty}\left(2n+1\right)\mathrm{Re}\left(a_n+b_n\right) \tag{4}$$

Where, n is the number of aerosol particles, a_n and b_n are the Mie coefficients.

The complex refractive index of soot aerosol particles, m the various types of aerosol particles given in [14] the standard radiative atmosphere model proposed by the International Association for Meteorology and atmospheric physics, are shown in Table 2.

Table 2 Complex refractive index of four types of aerosol particle

Wavelength/nm	Oceanic	Dust-like	Soot	Water-solube
400	$1.385-9.9\times10^{-9}\mathrm{i}$	$1.53-8.0\times10^{-3}\mathrm{i}$	$1.75-4.6\times10^{-1}\mathrm{i}$	$1.53-5.0\times10^{-3}\mathrm{i}$
488	$1.382-6.4\times10^{-9}\mathrm{i}$	$1.53-8.0\times10^{-3}\mathrm{i}$	$1.75-4.5\times10^{-1}\mathrm{i}$	$1.53-5.0\times10^{-3}\mathrm{i}$
550	$1.381-4.3\times10^{-9}\mathrm{i}$	$1.53-8.0\times10^{-3}\mathrm{i}$	$1.75-4.4\times10^{-1}\mathrm{i}$	$1.53-6.0\times10^{-3}\mathrm{i}$
694	$1.376-5.0\times10^{-9}\mathrm{i}$	$1.53-8.0\times10^{-3}\mathrm{i}$	$1.75-4.3\times10^{-1}\mathrm{i}$	$1.53-7.0\times10^{-3}\mathrm{i}$

Experiment $\lambda = 0.488\mu\mathrm{m}$. When the optical signal is transmitted between the stars and the ground, the energy attenuation produced by the soot aerosol can be expressed as [15]:

$$E = E_0 \exp\left(-k_{ext} \cdot d\right) \tag{5}$$

Where, E is the energy of the quantum signal transmitted through the soot aerosol, E_0 is the initial energy of the quantum signal, and d is the transmission distance of the quantum signal.

The link attenuation factor can be obtained by logarithmic formula (*5*), and the link attenuation factor can be expressed as:

$$L_{att} = 10 \cdot k_{ext} \cdot \lg e \cdot d \tag{6}$$

Ignoring the influence of other particles in the atmosphere, the link attenuation is related to the transmission distance and the concentration of aerosol particles as shown in Fig1. As can be seen from Fig. 1, when the transmission distance is constant, the attenuation of the link increases with the increase of the particle concentration, and reaches a maximum value of $0.89\mathrm{dB/km}$ at $n_0 = 3.9\times10^6/\mathrm{m}^3$ and $d = 9.6\mathrm{km}$, when the transmission distance is $3\mathrm{km}$, if the particle concentration increases from $2.1\times10^6/\mathrm{m}^3$ to $3.2\times10^6/\mathrm{m}^3$, the link attenuation increases from $0.3\mathrm{dB/km}$ to $0.46\mathrm{dB/km}$. Therefore, with the increase of aerosol concentration and the increase of transmission distance, the link attenuation will increase. The quantum communication link will be greatly affected by the two factors. The attenuation of the link can be reduced and the communication quality can be improved by adjusting the number of photon pulses at the transmitting end or choosing a better transmission environment.

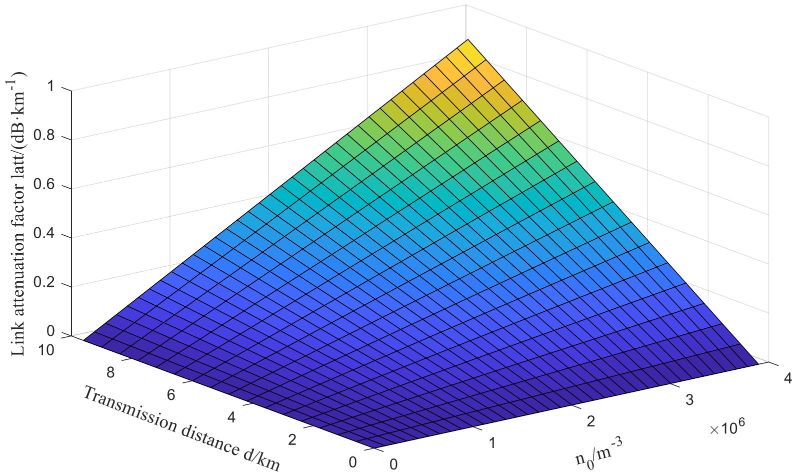

Fig. 1 Relationship between the concentration of soot aerosol particles, the transmission distance and the attenuation of the link

III. INFLUENCE OF SOOT AEROSOL ON THE CAPACITY OF QUANTUM COMMUNICATION CHANNEL

In the process of quantum signal transmission, the coherence of the quantum state will be destroyed by the interaction between the soot aerosol and the quantum state. The influence of the soot aerosol on the capacity of the communication channel is studied by selecting the amplitude damping channel.

From reference [16], the operator of amplitude-damped channel is:

$$F_k = \sum_n \sqrt{\binom{n}{k}} \sqrt{(1-p)^{n-k} p^k} \, |n-k\rangle\langle n| \tag{7}$$

Where, $\langle n|$ represents the eigen state of the soot aerosol environment operator, n represents the real part of the complex refractive index m, which is the scattering incident radiation ability of the soot aerosol, and $|k\rangle$ represents the eigen state of the soot aerosol quantum system, k represents the imaginary part of the complex refractive index m, which is the ability of the soot aerosol to absorb incoming radiation; p represents the probability of losing photons due to the influence of the soot aerosol in the transport of the quantum state [15], can be expressed as:

$$P = \frac{E_1 - E_2}{E_1} = 1 - \mathrm{e}^{-k_{ext} \cdot d} \tag{8}$$

Where, E_1 is the initial energy of the quantum signal, and E_2 is the energy of the quantum signal after the transmission distance d.

A quantum state in a single-photon-bit state can be defined as:

$$\boldsymbol{\rho} = \begin{pmatrix} \alpha_1 & \alpha_2 \\ \alpha_2^* & \alpha_3 \end{pmatrix} \tag{9}$$

Where, α_2^* represents the complex transformation of α_2. When the quantum state evolves through a damped amplitude channel, it is represented as:

$$\varepsilon(\boldsymbol{\rho}) = \begin{bmatrix} 1-(1-p)(1-\alpha_1) & \alpha_2\sqrt{1-p} \\ \alpha_2^*\sqrt{1-p} & \alpha_3\sqrt{1-p} \end{bmatrix} \tag{10}$$

Where, p_i represents the probability that the system is in $\boldsymbol{\rho}_i$ when the source is $\{p_i, \boldsymbol{\rho}_i\}$, where $\Sigma p_i = 1$, and under the action of the soot aerosol, when the input character are $\boldsymbol{\rho}_1 = |0\rangle\langle 0|$ and $\boldsymbol{\rho}_2 = |1\rangle\langle 1|$, the quantum system evolves into:

$$\varepsilon(\boldsymbol{\rho}) = \varepsilon\left(\sum_i p_i \boldsymbol{\rho}_i\right) = \varepsilon\left[p_1 \boldsymbol{\rho}_i + (1-p_1)\boldsymbol{\rho}_2\right] = \begin{bmatrix} p(1-p_1)+p_1 & 0 \\ 0 & (1-p)(1-p_1) \end{bmatrix} \tag{11}$$

The Von Neumann entropy of a quantized system can be expressed as:

$$f\left[\varepsilon\left(\sum_i p_i \boldsymbol{\rho}_i\right)\right] = -\left\{\left[p(1-p_1)+p_1\right] log_2\left[p(1-p_1)+p_1\right] + (1-p)(1-p_1) log_2\left[(1-p)(1-p_1)\right]\right\} \tag{12}$$

The channel capacity of a damped amplitude channel [17] can be expressed as:

$$C = \max\left\{f\left[\varepsilon\left(\sum p_i \boldsymbol{\rho}_i\right)\right] - \sum p_i f\left(\varepsilon\left(\boldsymbol{\rho}_i\right)\right)\right\} \tag{13}$$

The derivation of channel capacity can be expressed as:

$$p_1 = \frac{y(1-p)-p}{(1+y)(1-p)} \tag{14}$$

Where, y is:

$$y = 2^{\frac{H(p)}{1-p}} \tag{15}$$

The maximum capacity of an amplitude-damped channel can be expressed as:

$$C = \max\left\{-\left\{\left[p_1+(1-p_1)p\right]\log_2\left[p_1+(1-p_1)p\right]+(1-p)(1-p_1)\log_2\left[(1-p)(1-p_1)\right]\right\}-(1-p_1)H(p)\right\} \tag{16}$$

Ignoring the influence of other particles in the atmosphere, the relation between the capacity of the amplitude damping channel and the transmission distance and the aerosol concentration of the soot particles is shown in Fig2. As can be seen from Fig2, the channel capacity increases first and then decreases with the increase of transmission distance and aerosol particles, and the maximum of the channel capacity is 1.0819. When the transmission distance is 6km and the particle concentration is $2.1\times10^6/\text{m}^3$, $2.7\times10^6/\text{m}^3$ and $3.9\times10^6/\text{m}^3$, the channel capacity first increases from 1.08 to 1.0809, then decreases to 1.0804. When the particle concentration is $3.2\times10^6/\text{m}^3$ and the transmission distance is 3km, 6km and 9km, the channel capacity first increases from 1.0706 to 1.0819, and down to 1.0742. The transmission distance and the concentration of soot aerosol particles have great influence on the channel capacity of the amplitude-damped channel, which will make the transmission deviation of the key distribution system.

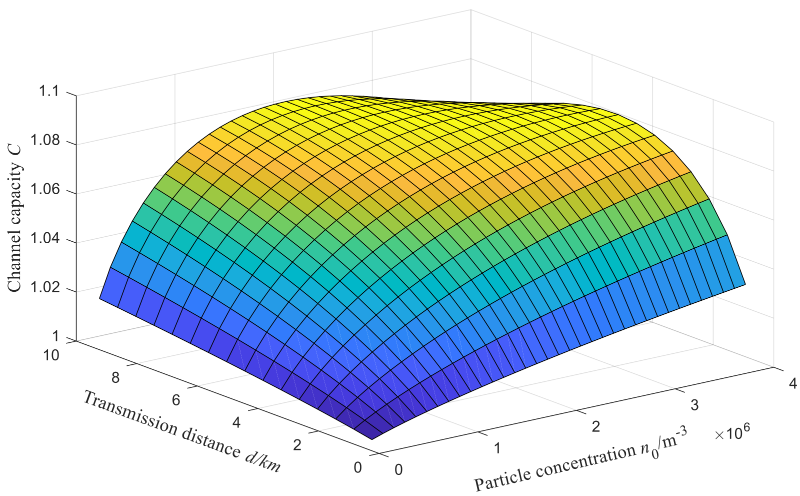

Fig. 2 Relationship among aerosol particle concentration, transmission distance and channel capacity

IV. INFLUENCE OF SOOT AEROSOL ON FIDELITY OF QUANTUM CHANNEL

The fidelity of the communication system is used to describe the similarity between the output state and the initial state of the quantum signal. In this paper, the relationship between the average fidelity of the amplitude-damped channel and the channel survival function is studied. The average fidelity of the quantum channel [18] can be expressed as under the influence of aerosol particles

$$B(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)=B\left(\sum_i p_i\boldsymbol{\rho}_i,\varepsilon\left(\sum_i p_i\boldsymbol{\rho}_i\right)\right)=tr\sqrt{\left(\sum_i p_i\boldsymbol{\rho}_i\right)^{\frac{1}{2}}\varepsilon\left(\sum_i p_i\boldsymbol{\rho}_i\right)\left(\sum_i p_i\boldsymbol{\rho}_i\right)^{\frac{1}{2}}} \quad (17)$$

Where, $tr(\cdot)$ is the matrix trace, $\boldsymbol{\rho}_1$ is the density matrix of the destination information, and $\boldsymbol{\rho}_2$ is the density matrix of the quantum state signal with surge.

The average fidelity of the quantum channel obtained by the amplitude-damped channel is:

$$B_z=\sqrt{\frac{\left(p+2(1-p)p_1\right)p_1}{2}}+\sqrt{\frac{\left(p+2(1-p)(1-p_1)\right)(1-p_1)}{2}} \quad (18)$$

Where, p_1 and p_2 represent the probabilities of the output characters $|0\rangle$ and $|1\rangle$, respectively.

The probability $p_1=0.1$ when the quantum state of the system is in $\boldsymbol{\rho}_1$ is selected to simulate the fidelity of the amplitude damping channel. The fidelity and transmission distance of the amplitude-damped channel and the concentration of soot particles are shown in Fig3. Ignoring the influence of other particles in the atmosphere, the channel fidelity decreases with the increase of the concentration of particles when the transmission distance remains constant, the channel fidelity decreases gradually. When the transmission distance is $d=9.6\text{km}$ and $n_0=3.9\times10^6/\text{m}^3$, the fidelity reaches the minimum value 0.78. When the transmission distance and particle concentration are fixed, the change of fidelity is more obvious. When the particle concentration is $n_0 = 2.7\times10^6 / \mathrm{m}^3$, the transmission distance increases from $d = 3\mathrm{km}$ to $d = 9\mathrm{km}$, and the fidelity changes from 0.98 to 0.83.The greater the transmission distance and the concentration of soot aerosol particles, the more obvious the influence on the fidelity, and the more serious the distortion of the received quantum signal. Based on the known particle concentration and transmission distance, the channel bandwidth or the photon emission power can be adjusted to improve the fidelity and the quality of the received signal.

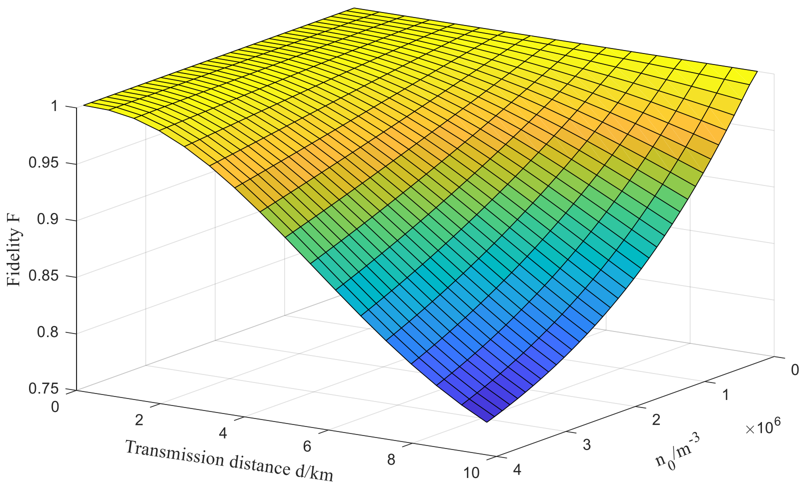

Fig. 3 Relationship among aerosol particle concentration, transmission distance and channel fidelity

V. INFLUENCE OF SOOT AEROSOL ON CHANNEL BIT ERROR RATE (BER) OF QUANTUM SYSTEM

When the optical signal is transmitted between the satellite and the ground, it will be affected by the soot aerosol particles. The channel error rate (Ber) of quantum system is used to describe the precision of quantum information transmission in a certain time, can be expressed as the ratio of the received bit error rate (Ber) to the total bit error rate [19], denoted as:

$$W_b = \frac{W_e}{W_s} \tag{19}$$

Where, W_b represents the bit error rate (Ber) caused by soot aerosol, W_e represents the received bit error rate, and W represents the total bit error rate.

According to BB84 protocol [20], the received bit error rate (Ber) W_e can be expressed as:

$$W_e = \eta n_a \left(1 - a\right) \mathrm{e}^{-4\eta n_a} + a\eta n_a \mathrm{e}^{-\eta G} \tag{20}$$

Where, η represents the quantum efficiency of the single-photon avalanche diode; a represents the depolarization effect factor caused by the soot aerosol; $G = 4n_a + \mathrm{e}^{-k_{ext}d}$; n_a is the number of photons detected by the receiver, denoted as:

$$n_a = \frac{n_b}{2} + n_c \tag{21}$$

Where, n_b represents the photon count caused by background noise, and n_c represents the dark current index of the photodetector.

The total bit rate W_s is:

$$W_s = F_s R_r \left[1 - \exp\left(-\beta\delta\tau T_a \eta H_c\right)\right] \tag{22}$$

Where, F_s is the screening factor, R_r is the repetition rate of the transmitted pulses, β is the average photon number per pulse, δ is the depolarization channel transmission factor, $\delta = 10^{-0.1L_{att}\theta}$ is the transmission factor, where θ is the zenith angle from the ground to the satellite; τ represents the single photon capture rate; T_a represents the transmission rate of the system device; H_c represents the measurement factor. The values of each parameter on the channel BER are shown in Table 3.

Table 3 Channel bit error rate (Ber) parameter

η	n_a	n_b	F_s	R_r	β	τ	T_a	H_c

0.65	10^{-3}	10^{-6}	0.5	0.5	1	0.5	1	1

The experiment selected $\lambda = 0.488\mu m$ for simulation. The relationship between bit error rate (Ber) of satellite-to-ground quantum communication link system and transmission distance and aerosol concentration of soot particles is shown in Fig4. As can be seen from Fig4, under the influence of soot aerosol particles, when the transmission distance is fixed, with the increase of the concentration of soot particles, the soot particles interact with the quantum signal, the bit error rate (Ber) increases gradually, and increases with the increase of transmission distance when the concentration of soot particles is constant. When the transmission distance is more than $4.2km$ particles and the concentration is more than $2.1\times10^{6}/m^{3}$, the bit error rate changes obviously. When the transmission distance is $d = 9.6km$ and $n_0 = 3.9\times10^{6}/m^{3}$, the maximum bit error rate is 0.2379. When the transmission distance is $9km$, the particle concentration increases from $2.1\times10^{6}/m^{3}$ to $3.2\times10^{6}/m^{3}$, and the bit error rate (Ber) increases from 0.0326 to 0.0960. When the transmission distance is $3km$, the particle concentration increases from $2.1\times10^{6}/m^{3}$ to $3.2\times10^{6}/m^{3}$, and the BER increases from 0.0087 to 0.0122. Therefore, the greater the transmission distance and the concentration of soot aerosol particles, the more obvious the impact on bit error rate.

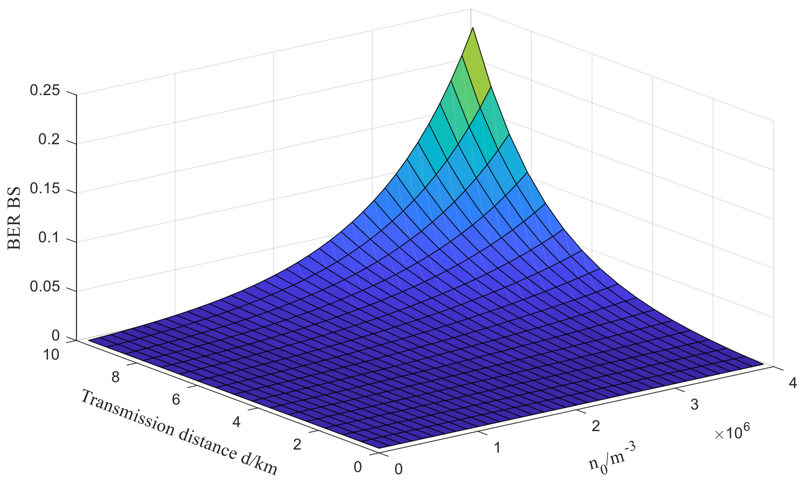

Fig. 4 Relationship among aerosol particle concentration, transmission distance and channel bit error rate

VI. CONCLUSION

In this paper, the influence of soot aerosol on the quantum communication performance between satellite and ground is studied. According to the size distribution parameters and complex refractive index of soot aerosol, the extinction coefficient of soot aerosol particles is calculated, and the influence of soot aerosol on the attenuation is analyzed. Aiming at the amplitude-damped channel, the relationships among the soot aerosol particle concentration, the transmission distance, the channel capacity, the channel fidelity and the channel bit error rate are simulated. The simulation results show that the amplitude damping channel capacity and channel fidelity decrease with the increase of soot aerosol concentration when the transmission distance is constant, link attenuation and channel bit error rate (Ber) are on the rise in different degrees. Therefore, the influence of soot particles on the quantum communication can be used as a theoretical reference. The parameters can be adjusted to ensure the normal transmission of quantum signal.

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