Journal of Computer and Communications, 2024, 12, 191-201
https://www.scirp.org/journal/jcc
ISSN Online: 2327-5227
ISSN Print: 2327-5219

# Research on the Performance of Non-Line-of-Sight Ultraviolet Communication in Rain and Fog Environment

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**How to cite this paper:** Zhang, S.Q. (2024) Research on the Performance of Non-Line-of-Sight Ultraviolet Communication in Rain and Fog Environment. *Journal of Computer and Communications*, **12**, 191-201.
https://doi.org/10.4236/jcc.2024.128012

**Received:** July 23, 2024
**Accepted:** August 26, 2024
**Published:** August 29, 2024



## Abstract

Wireless ultraviolet communication is a new type of communication mode. It refers to the transmission of information through the scattering of ultraviolet light by atmospheric particles and aerosol particles. The scattering characteristics can enable the wireless ultraviolet communication system to transmit ultraviolet light signals in a non-line-of-sight manner, which overcomes the weakness that other free space optical communications must work in a line-of-sight manner. Based on the basic theory of scattering and absorption in atmospheric optics, taking the ultraviolet light with a wavelength of 266 nm as an example, this paper introduces the classical model of non-line-of-sight single-scattering coplanarity based on the ellipsoid coordinate system. The model is used to simulate and analyze the relationship between the geometric parameters such as transmission distance, transceiver elevation angle and transceiver half-angle and the received optical power per unit area. The performance of non-line-of-sight ultraviolet communication system in rain and fog environment is discussed respectively. The results show that the transmission quality of non-line-of-sight ultraviolet atmospheric propagation is greatly affected by the communication distance. As the distance increases, the received light power per unit area gradually decreases. In addition, increasing the emission elevation angle, the receiving elevation angle and the receiving half angle is an important way to improve the system performance.

## Keywords

Ultraviolet Light, Single Scattering, Optical Scattering Communication, NLOS, MATLAB

## 1. Introduction

In recent years, the application of ultraviolet technology in civil and military fields has gradually become widespread. Wireless ultraviolet communication has attracted people's attention because it can transmit information in complex communication environments. At the same time, ultraviolet light sources and ultraviolet detectors are also developing rapidly, but the key technologies of ultraviolet communication need to be broken through. Ultraviolet NLOS scattering communication channel modeling and ultraviolet photon detection have become the key issues of ultraviolet communication, because it needs to consider the complex and changeable atmospheric environment conditions and the geometric configuration parameters of ultraviolet light source transceiver devices [1]. In view of the above problems, considering that rainy and foggy weather is a common meteorological condition, this paper studies the construction of non-line-of-sight wireless optical communication model under rainy and foggy weather and the influence of geometric parameters on communication quality, so as to provide theoretical basis for improving the performance of communication system. Due to the strong scattering characteristics of the ultraviolet band in the atmosphere, it is an ideal choice for non-line-of-sight communication [2]. Ultraviolet light is a general term for the wavelength of in the electromagnetic spectrum. In the wavelength range higher than 280 nm, the performance of most optical systems will be limited due to too strong radiation. In the wavelength range lower than 200 nm, the strong absorption of oxygen molecules leads to serious limitation of transmission and inability to communicate. The band of is called the "solar blind" band. The solar radiation in this band is strongly absorbed by ozone molecules in the stratosphere. There is almost no solar radiation in this band in the near-ground atmosphere [3], so the influence of sunlight on the communication system is very small. The communication environment can be approximated as a background noise-free environment. Therefore, the ultraviolet light in this band is used for communication, which has the advantages of strong anti-interference ability and can work all-weather. The shorter the wavelength of ultraviolet light is, the stronger the scattering effect is. Therefore, atmospheric particles will have a strong scattering effect on the ultraviolet light in the "solar blind" section, which is beneficial to the improvement of the received light power at the receiving end [4]. In addition, ultraviolet communication can be divided into line-of-sight (LOS) and non-line-of-sight (NLOS). Line-of-sight means that there is no obstacle between the transceivers of the ultraviolet communication system, and the ultraviolet signal can be directly received by the receiver. In most cases, the scene where the direct link is blocked is more common, which requires the signal to bypass the obstacles between the transceivers, so there is a non-line-of-sight mode. In this paper, the non-line-of-sight single scattering communication is analyzed by taking the radiation wavelength of 266 nm in the solar blind spectral region of the mid-ultraviolet band as an example. The non-line-of-sight communication of ultraviolet light takes the low-altitude atmosphere as the transmission medium. The light signal at the transmitting end changes the transmission direction through the scattering of ultraviolet light by atmospheric molecules and aerosol particles. Therefore, its communication quality is greatly affected by atmospheric conditions. Rain and fog weather are common meteorological conditions. A large number of aerosol particles are suspended in the air under these low-visibility weather conditions. The scattering of aerosol particles and ultraviolet photons can change the motion direction of photons when transmitted in the atmospheric channel, so as to realize the non-line-of-sight transmission of ultraviolet signal [5]. Atmospheric molecules in the rain and fog environment absorb the ultraviolet signal in the air, so that the energy is attenuated. Therefore, studying the quality of non-line-of-sight ultraviolet communication in different atmospheric environments can provide a theoretical basis for improving the channel performance of ultraviolet communication. Ultraviolet communication technology is still an emerging field to be explored. It has unique advantages that cannot be replaced and complemented by other means such as radio communication and infrared line-of-sight communication, and has good application prospects [6]. However, key technologies such as communication distance and transmission rate are also waiting to be solved [7].

## 2. The Establishment of Channel Model

In 1979, Reilly established a model of single scattering transmission of wireless ultraviolet light through the atmospheric channel based on the ellipsoid coordinate system. In 1991, Luettgen proposed a wireless ultraviolet non-line-of-sight coplanar single scattering communication model based on the ellipsoid coordinate system based on Reilly [8]. Based on this model, the simulation curve of the received optical power per unit area is obtained by changing the geometric parameters of the system such as the elevation angle and divergence angle of the transceiver, and the influence on the non-line-of-sight ultraviolet transmission performance is studied. The model of ultraviolet NLOS single scattering communication system is shown in "**Figure 1**" [9]. In the single scattering transmission model, only one scattering effect is considered for the optical transmission process, and the occurrence of multiple scattering is ignored, which simplifies the calculation of the model. In the figure, the transmitter $F_1$ emits the ultraviolet light signal with the emission elevation angle $\beta_T$ and the emission half angle $\theta_T$. The receiver $F_2$ receives the ultraviolet light signal with the receiving elevation angle $\beta_R$ and the receiving half angle $\theta_R$. $V$ is the effective scatterer, which is the intersection of the transmitting cone and the receiving cone. This area is the scattering effective area that can reach the receiving end. P is a point in the effective scattering body, $\theta_S$ is the scattering angle, and $\theta_S = \beta_T + \beta_R$, r is the horizontal distance between the transmitter and receiver. The single scattering model of ultraviolet light is analyzed by using the long spherical coordinate system. The ellipsoid coordinate system is shown in "**Figure 2**". The long ellipsoid is the surface generated by the rotation of the ellipse around its long axis. The oblate ellipsoid is generated by rotating around the short axis. Any point on the ellipsoid can be uniquely determined by the radial coordinate $\xi$, the angular coordinate $\eta$, and the azimuth angle $\phi$. Any point in the three-dimensional space rectangular coordinate system space composed of xoy can also be represented in the long spherical coordinate system. Because the distance between the focal points passing through any point on the prolate ellipsoid is constant, if the transmitter and receiver are located on the two focal points of the prolate sphere respectively, and the speed of light in the medium is constant, then the prolate ellipsoid can be considered as a uniform scattering surface.

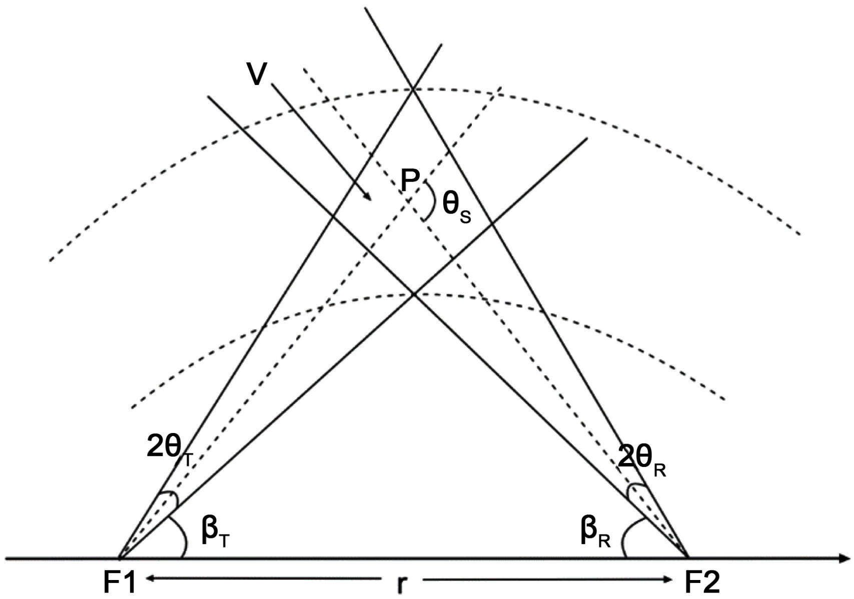


Figure 1. Non-line-of-sight ultraviolet communication link diagram.

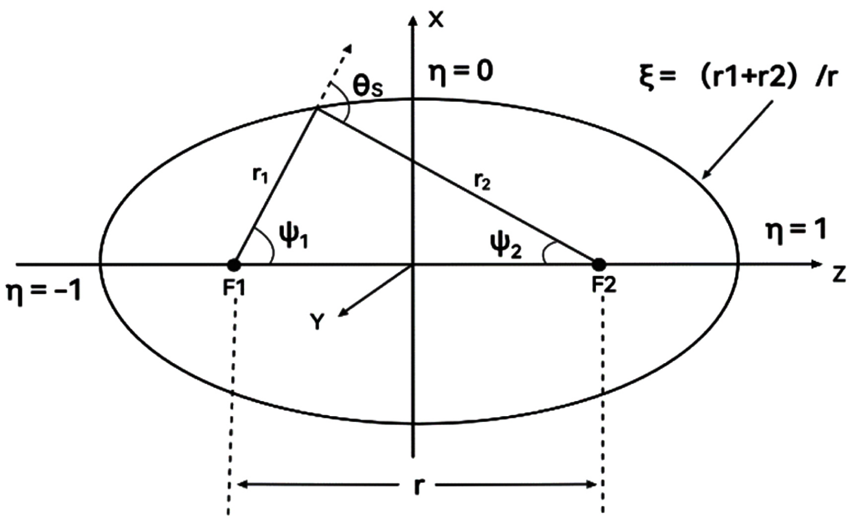


Figure 2. Ellipsoidal coordinate system diagram.

At time $t = 0$, the emission end emits photons with energy $E_t$. Assuming that the photons are uniformly distributed in the cone with a half emission angle of $\theta_T$, the corresponding solid angle of the emission cone is $\Omega = 4\pi\sin^2\frac{\theta_T}{2}$, and the energy emitted per unit solid angle is $\frac{E_t}{\Omega}$. The photons transmit $r_1$ distance in the emission cone, and reach point P in the scattering body after the transmission time of $t = r_1/c$. The energy at point P is $H_p = \frac{E_t e^{-k_e r_1}}{\Omega r_1^2}$, where $k_e$ is the extinction coefficient of the atmosphere. is equal to the sum of the scattering coefficient $k_s$ and the absorption coefficient $k_a$. The photon interacts with atmospheric molecules and aerosol particles at the P point. It can be considered that the space contained in the volume micro-element $\delta v$ of the P point is a secondary light source, and the energy it scatters in the space is $\delta E_p = k_s H_p \delta v$. After introducing the scattering phase function, the energy contained in the unit scattering solid angle from the P point to the receiving end is $\delta R_P = \delta E_p \frac{P(\cos\theta_s)}{4\pi}$. The energy scattered by this secondary light source can be received by the receiving system at $t = (r_1 + r_2)/c$. The total energy density received from the secondary light source at the receiving end is

$\delta E_r = \delta R_P \frac{e^{-k_e r_2}}{r_2^2} \cos(\zeta)$, $\zeta$ is the angle between the line connecting the secondary light source and the receiving end and the axis of the receiving field of view. When the transmitting and receiving half angles are small and the spatial scattering volume is not large, $\zeta$ can be considered as 0, so

$\delta E_r = \frac{k_s E_t p(\cos\theta_s) e^{-k_e(r_1+r_2)}}{4\pi\Omega(r_1^2 r_2^2)} \delta v$. The scattering volume element in the long spherical coordinate system is $\delta v = \frac{r^3}{8}(\xi^2 - \eta^2)\delta\xi\delta\eta\delta\phi$. Substituting $\delta v$ into it, the energy per unit area of the receiver can be obtained as

$\delta E_r = \frac{k_s E_t p(\cos\theta_s) e^{-k_e \xi(r_1+r_2)}}{2\pi r\Omega(\xi^2 - \eta^2)} \delta\xi\delta\eta\delta\phi$. The energy scattered by the surface will reach the receiver at $t = \frac{r_1 + r_2}{c}$. Then $\xi = \frac{ct}{r}$ and $\delta\xi = \frac{c\delta t}{r}$ can be obtained from $\xi = \frac{r_1 + r_2}{r}$. Substituting the two formulas into the above formula and integrating them on the surface of the long sphere, the irradiance received by the receiving end at the time $t = \frac{\xi r}{c}$ is obtained [10]:

$$E(\xi) = \begin{cases} 0 & \xi < \xi_{\min} \\ \frac{E_t c k_s e^{-k_e \xi(r_1+r_2)}}{2\pi\Omega r^2} \int_{\eta_1(\xi)}^{\eta_2(\xi)} \int_{\phi_1(\xi,\eta)}^{\phi_2(\xi,\eta)} \frac{P(\cos\theta_s)}{\xi^2 - \eta^2} \mathrm{d}\phi \mathrm{d}\eta & \xi_{\min} \le \xi \le \xi_{\max} \\ 0 & \xi > \xi_{\max} \end{cases} \quad (1)$$

## 3. Scattering Phase Function

In NLOS ultraviolet communication, ultraviolet photons are finally received by the receiving end through the absorption and scattering of the atmosphere.

Therefore, studying the influence of absorption and scattering on photons is a crucial part of studying the performance of NLOS ultraviolet communication. The atmosphere is not all gas, but also contains some small particles of solid and liquid, which are collectively referred to as aerosol particles. Atmospheric particles will absorb light of various wavelengths propagating in it. As the transmission distance increases, the energy of photons will gradually decrease. Therefore, the absorption of the atmosphere will limit the transmission distance of the communication system. NLOS ultraviolet light is mostly used for short-distance communication. When ultraviolet light is transmitted in the atmosphere, it usually undergoes Rayleigh scattering and Mie scattering. When the particle size in the atmosphere is much smaller than the wavelength of the incident light, Rayleigh scattering plays a leading role [11]. The Rayleigh scattering phase function can be expressed as:

$$P_R\left(\cos\theta_s\right)=\frac{3\left[1+3\gamma+(1-\gamma)\cos^2\theta_s\right]}{4(1+2\gamma)} \quad (2)$$

When the difference between the wavelength and the particle diameter is small or the particle diameter is larger than the wavelength of ultraviolet light, it can be treated by Mie scattering. The Mie scattering phase function can be expressed as:

$$P_M\left(\cos\theta_s\right)=\left(1-g^2\right)\left[\frac{1}{\left(1+g^2-2g\cos\theta_s\right)^{3/2}}+f\frac{0.5\left(3\cos^2\theta_s-1\right)}{\left(1+g^2\right)^{3/2}}\right] \quad (3)$$

When ultraviolet light is transmitted in the atmosphere, it is the result of the combined action of Rayleigh scattering and Mie scattering. Therefore, the scattering phase function in this paper is the weighted sum of Rayleigh scattering phase function and Mie scattering phase function. The scattering phase function in this paper can be expressed as:

$$P\left(\cos\theta_s\right)=\frac{k_{sca}^m}{k_{sca}}P_R\left(\cos\theta_s\right)+\frac{k_{sca}^a}{k_{sca}}P_M\left(\cos\theta_s\right) \quad (4)$$

In the UV scattering work, *r*, *f* take 0.017, 0.5. $k_{sca}^m$ is the Rayleigh scattering coefficient, $k_{sca}^a$ is the Mie scattering coefficient, and the value of g is related to the weather. Under fog and rain weather conditions, *g* is 0.9 and 0.93 respectively [12].

## 4. Analysis of NLOS Ultraviolet Light Transmission Performance in Rain and Fog Environment

In this paper, the radiation wavelength of 266 nm in the solar-blind spectral region of the mid-ultraviolet band is taken as an example. The transmission power is set to 1 W. When ultraviolet light is transmitted in rain or fog environment, the combined effect of Rayleigh scattering and Mie scattering is considered. The scattering coefficient and absorption coefficient of ultraviolet light transmitted in the atmosphere are simulated by Modtran software [13]. When the weather condition is rain, the absorption coefficient is $k_a = 1.86 \times 10^{-3}\ \text{m}^{-1}$, and the scattering coefficient is $k_s = 26.01 \times 10^{-3}\ \text{m}^{-1}$. When the weather condition is fog, the absorption coefficient is $k_a = 0.993 \times 10^{-3}\ \text{m}^{-1}$, and the scattering coefficient is $k_s = 19.56 \times 10^{-3}\ \text{m}^{-1}$. In non-clean weather, aerosol particles in the atmosphere occupy the main body, and their scattering of light is mainly characterized by Mie scattering [14], and the Rayleigh scattering coefficient is calculated to be $k_{sca}^{m} = 0.24 \times 10^{-3}\ \text{m}^{-1}$.

When the transmitting elevation angle and the receiving elevation angle are both set to 45˚ and the transmitting half angle and the receiving half angle are 10˚, the relationship between the received power per unit area and the communication distance is shown in "**Figure 3**". It can be seen from the simulation results that under two weather conditions, the received optical power per unit area decreases gradually with the increase of communication distance. In addition, there are some differences in the transmission performance of ultraviolet light under rainy and foggy weather conditions. The received light power per unit area in rainy days is higher than that in foggy days, that is to say, under the parameters selected in this paper, rainy days are more suitable for non-line-of-sight ultraviolet communication. This is consistent with the conclusion that the path loss gradually increases with the increase of communication distance in the reference [15].

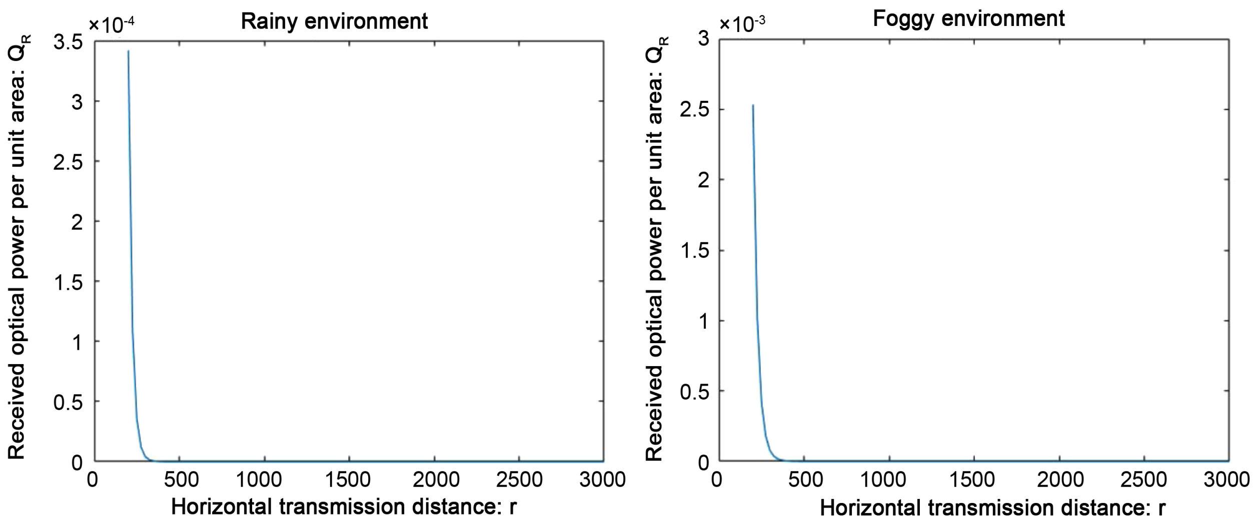


**Figure 3.** Relationship between received optical power per unit area and communication distance in NLOS UV communication.

The horizontal distance between the transmitting end and the receiving end is set to 500 m, and the transmitting half angle and the receiving half angle are 5˚. When the receiving elevation angle range is 5˚ - 90˚, the variation curve of the received light power per unit area with the receiving elevation angle is observed when the transmitting elevation angle is 20˚, 40˚, 60˚ and 80˚. The simulation results are shown in "**Figure 4**". The results show that when the transmitting elevation angle is 20˚, the communication quality is the best. As the transmitting elevation angle gradually increases, the received optical power per unit area gradually decreases, and the communication quality gradually deteriorates. When NLOS communication is carried out in rainy and foggy weather conditions, the elevation angles of transmitting and receiving should be reduced as much as possible. When the emission elevation angle range is 5˚ - 90˚, the variation curve of the received light power per unit area with the emission elevation angle is observed when the receiving elevation angle is 20˚, 40˚, 60˚ and 80˚. The simulation results are shown in "Figure 5". The communication quality in the fog environment is better than that in the rain environment. With the increase of the transmitting elevation angle, the received optical power per unit area decreases. When the transmitting elevation angle and the receiving elevation angle are in the range of 0˚ - 20˚, the path loss is small and the communication quality is high. This is consistent with the conclusion of the literature [16].

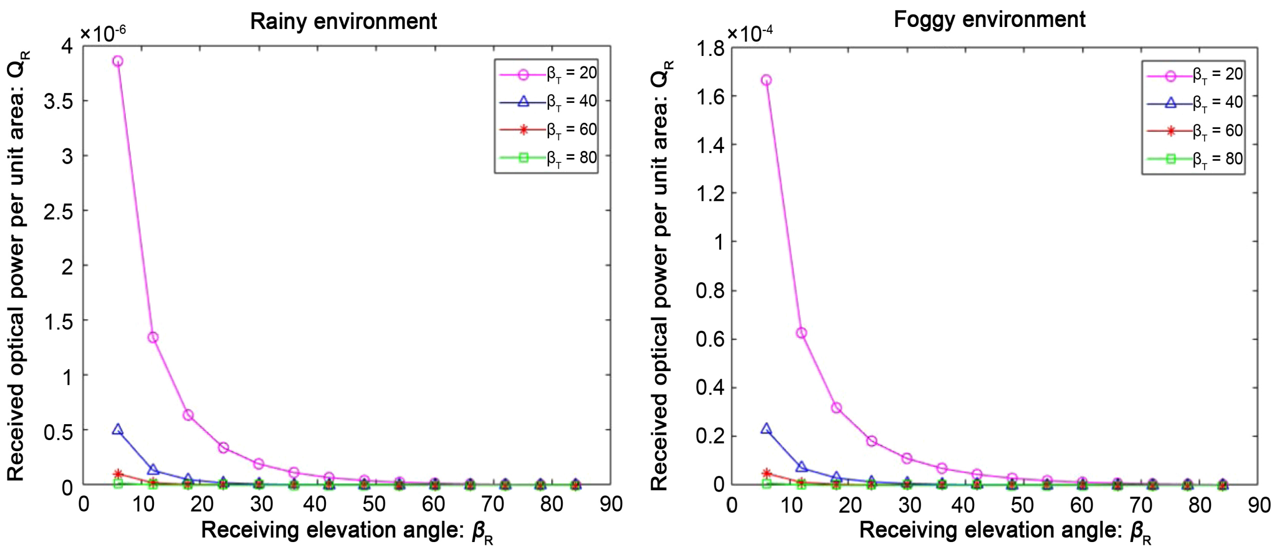


**Figure 4.** Relationship between received optical power per unit area and received elevation angle in NLOS UV communication.

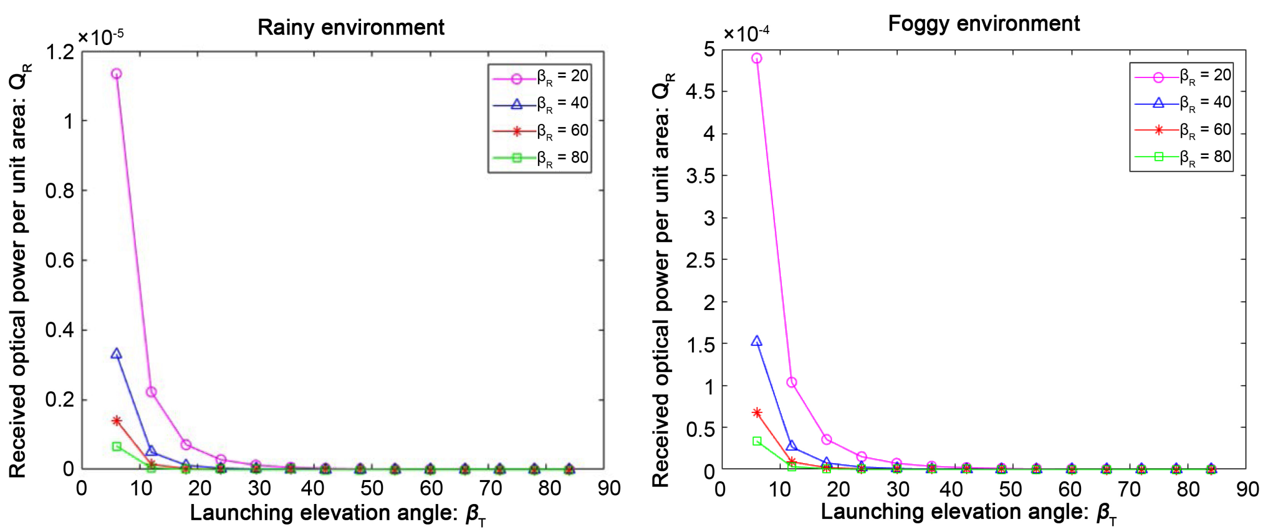


**Figure 5.** The relationship between the received optical power per unit area and the emission elevation angle of NLOS UV communication.

The horizontal distance between the transmitting end and the receiving end is 500 m, and the transmitting elevation angle and the receiving elevation angle are both 50˚. When the transmitting half angle is 15˚, 25˚ and 35˚ respectively, the receiving half angle is set to range from 0˚ - 45˚, and the relationship between the receiving optical power and the receiving half angle is observed. The simulation curve is shown in "Figure 6". When the receiving half angle is 15˚, 25˚ and 35˚ respectively, the range of the transmitting half angle is set to 0˚ - 45˚, and the relationship between the receiving optical power and the transmitting half angle is viewed. The simulation curve is shown in "Figure 7". When the emission half angle is a fixed value, the received optical power per unit area increases with the increase of the receiving half angle. The increase of the receiving half angle will increase the volume of the common scatterer, and the probability of the photon being received by the receiving end after scattering will increase. At the same time, it also increases the number of photons reaching the receiving surface of the detector, thereby increasing the received optical power. The results are consistent with some conclusions in the literature [17]. For the selection of non-"solar blind" ultraviolet band communication system, increasing the receiving field of view will increase the system noise caused by background radiation while increasing the received light energy. When the receiving half angle is fixed, with the increase of the transmitting half angle, the receiving optical power per unit area decreases first and then increases, and there is a minimum value. Under the condition that the incident light power is constant, the increase of the emission half angle will reduce the signal strength and reduce the received light power per unit area, but it also increases the volume of the effective scatterer, resulting in an increase in the received light power per unit area. The combined effect of the two determines the communication performance of the system.

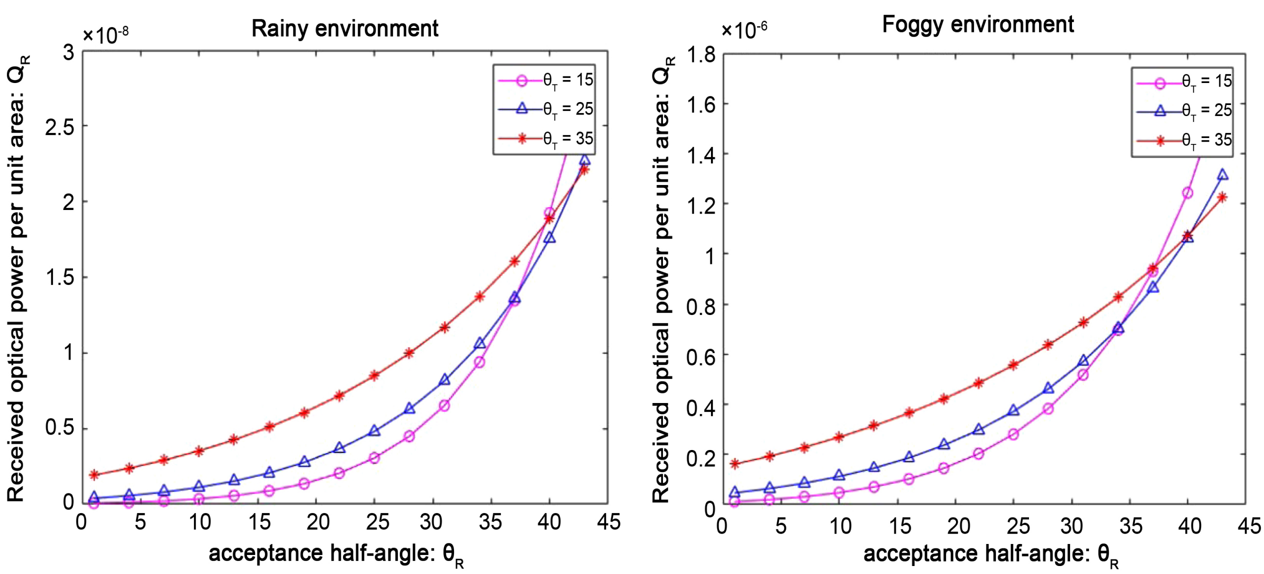


**Figure 6.** The relationship between the received optical power per unit area and the receiving half angle of NLOS ultraviolet communication.

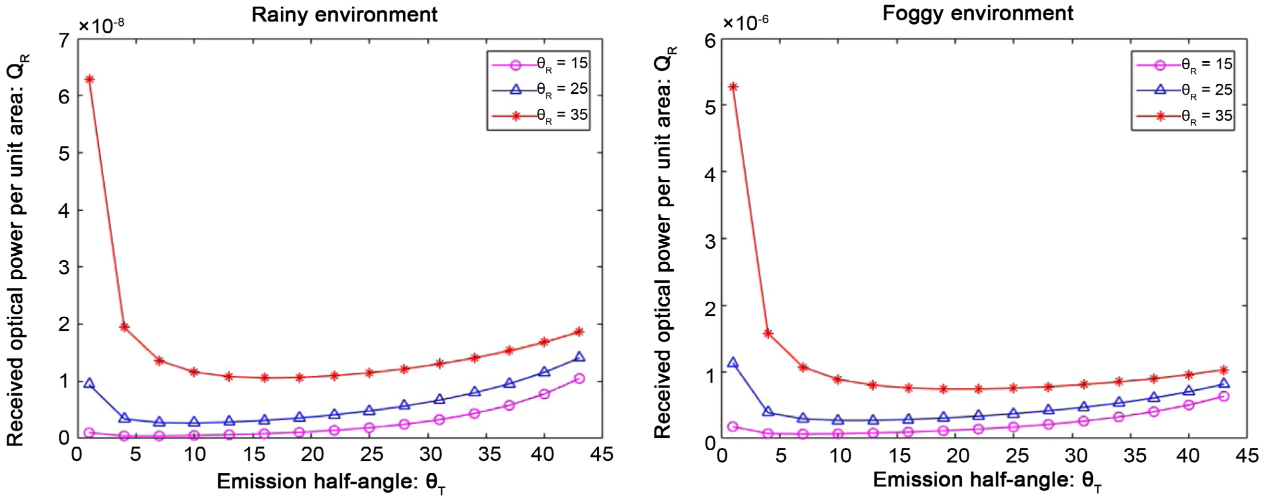


**Figure 7.** The relationship between the received optical power per unit area and the emission half angle of NLOS ultraviolet communication.

## 5. Conclusion

Based on the scattering and absorption of atmospheric molecules and aerosol particles, this paper simulates and analyzes the relationship between non-line-of-sight ultraviolet communication performance and communication distance, transceiver elevation angle and transceiver half angle under rain and fog weather conditions. The scattering characteristics of ultraviolet light make the ultraviolet light communication system inevitably affected by severe weather such as precipitation, snow, fog and haze. The single scattering model discussed in this paper is still applicable to other weather conditions, but some parameters need to be changed. When ultraviolet light is transmitted in rain and fog environment, the absorption and scattering of ultraviolet light by rain and fog particles seriously affect the system performance and communication distance of ultraviolet light communication. The results show that in the rain and fog environment, the larger the communication distance, the smaller the received optical power per unit area. In addition, reducing the transceiver elevation angle or increasing the receiving half angle is also a way to improve the signal quality of the non-line-of-sight ultraviolet communication system. The research results of this paper have certain guiding significance for the establishment of actual wireless ultraviolet communication systems and the performance improvement of communication systems in different scenarios, and provide theoretical basis for it.

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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