Analysis of UV Multiple Scattering Based on Improved MCI-PIS Model

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ABSTRACT Wireless ultraviolet communication uses the atmospheric scattering effect for signal transmission, and this paper improves the partially important sampling model (MCI-PIS) in the Monte Carlo integration method, and the improved model is used to simulate the influence of multiple system parameters such as communication distance, transceiver tilt angle, transceiver divergence angle on the path loss and impulse response of ultraviolet light communication. The simulation results show that the path loss of the improved model for multiple scattering of ultraviolet light is increased by 0.2-2 dB, and the impulse response is almost the same as that of MCI-PIS, but the calculation effect is increased by 20% compared with the MCI-PIS model.

INDEX TERMS UV light communication, multiple scattering, Monte Carlo, computational efficiency.

I. INTRODUCTION Wireless ultraviolet communication uses ultraviolet light in the “sun blind” band (200 nm-280 nm) as the information carrier and uses the scattering effect of the atmosphere on photons to communicate. It overcomes the disadvantages of free-space optical communication, which requires line-of-sight, and can adapt to more complex environments. It is because of the above advantages of UV light that UV communication has gradually become a hot research topic in the field of optical communication. The unique scattering propagation mode of UV light leads to unique channel model of UV communication. Before applying wireless UV communication system, it is necessary to study the channel model of UV communication and to analysis its performance under different system parameters.

A. RELATED WORK ON UV LIGHT TRANSMISSION MODELS The earliest channel model applied to UV communication is the Monte-Carlo simulation(MCS) model, which estimates the photon reception probability by counting the number of photons reaching the receiving end. However, this method requires simulation of a large number of photon counts and is inefficient, which is mainly applied to single scattering. In 2009, Ding et al. used a Monte-Carlo simulation method based on photon tracking, which captures the multiple scattering effect of UV photons and relaxes the assumption of single scattering theory. Then a stochastic non-line-of-sight(NLOS) UV communication channel model was developed to obtain the expected impulse response by photon reception probability and propagation delay [1]. In the following year, Ding et al. first proposed a NLOS path loss model using Monte-Carlo integration(MCI) method to find the path loss of multiple scattering and the contribution of each order of scattering, but failed to solve the impulse response function calculation problem [2]. Until 2019, Yuan Renzhi et al. improved the MCI method to solve the problem of calculating the impulse response of the system using the MCI model [4], and proposed three different sampling methods in [5], which greatly improved the computational efficiency of the MCI model. In [6], three methods were proposed to accelerate the MCI-PIS model in terms of both convergence speed and computational efficiency. In [7], a new simplified path loss(PL) model is proposed, which can accurately convert the triple integral in the single scattering PL model into a single integral, reducing the computational complexity and improving the effectiveness of the model. Besides, the proposed simplified model is in closed form compared to the spherical crown model. In [8], Yuan Renzhi et al. summarized...
the analytic channel model and probabilistic channel model for UV multiple scattering, and suggested that the MCS and MCI models can be combined to combine the advantages of both. In [9], a Monte-Carlo based UV multiple scattering model was developed, and the relationship between path loss and communication distance for spherical and non-spherical particles at different particle concentrations was analyzed using Mie scattering and T matrix. Although the current MCI-PIS model has great computational efficiency and convergence speed, higher performance Monte-Carlo models are still in demand.

B. CONTRIBUTION AND ORGANIZATION OF THIS PAPER
In this paper, an improved model based on the MCI-PIS model is proposed, and the concept of photon survival probability in the MCS model is introduced in the process of detailing the MCI-PIS model to update the probability of detection after $n$th scattering of photons. When it is necessary to consider the energy consumption of photons in transmission process, the calculation results using the improved model will be more accurate than the MCI-PIS model. To verify the correctness of the improved model, the path loss and impulse response curves of the improved model are compared with those of the MCI-PIS model, and it is found that the trend of the path loss curve of the improved model is similar to that of the MCI-PIS model, while the impulse response curves match. Then, in order to study the performance of the improved model under different parameters, different system parameters are set for simulation. Finally, the computational efficiency of the two models with different photons numbers and scattering orders is compared, and the results show that the computational efficiency of the improved model is improved by 20%.

The rest of the paper is organized as follows. In section 2, we give a detailed description of the MCI-PIS model and introduce the photon survival probability, giving the corresponding formula. Then, in section 3, the improved model is simulated and validated for three parts: path loss, impulse response and computational efficiency and the corresponding results are given. In section 4, some conclusions and a summary of the whole paper are presented.

II. ANALYSIS OF UV MULTIPLE SCATTERING BASED ON IMPROVED MCI-PIS MODEL
Ultraviolet light is transmitted by the scattering of ultraviolet light by particles such as particles, aerosols and dust in the atmosphere [2]. The short-range communication is mainly based on single scattering, but as the distance increases, the influence of multiple scattering has to be considered. The multiple scattering process is shown in Figure 1.

As can be seen from Figure 1, the transmitter is located at $(0, r, 0)$ and the receiver is located at $(0, 0, 0)$. The elevation, azimuth and divergence angles of the transmitter are $\theta_T$, $\phi_T$ and $\beta_T$, respectively. The elevation, azimuth and divergence angles of the receiver are $\theta_R$, $\phi_R$ and $\beta_R$, respectively, and $u_T$ and $u_R$ represent the direction cosine of the transmitter and receiver, respectively. We can use $(d_i, \theta_i, \phi_i)(i = 0, 1, 2, \ldots, n)$ to represent each order scattering process of the photon, where $i = 0$ represents the initial emission process of the photon. The position and direction cosine of the photon are represented by $L_i$ and $u_i$, respectively. $\theta_i$ and $\phi_i$ are the scattering elevation and azimuth between the direction cosine $u_i$ and $u_{i-1}$, while $\theta_0$ and $\phi_0$ are the scattering elevation and azimuth between the direction cosine $u_0$ and $u_T$ [5].

For the $i$th order scattering, the probability that the propagation direction of the photon after scattering is within the solid angle $d\Omega_i: = \sin\theta_i d\theta_i d\phi_i$ and the propagation distance is in the interval $(d_i, d_{i+1})$ is [5]:

$$dQ_i = f_{D}(d_i) f_{\Theta}(\theta_i) f_{\Phi}(\phi_i) dd_i d\theta_i d\phi_i$$

(1)

where $f_{D}(d_i)$ is the probability density function (PDF) of the transmission distance $d_i$, $f_{\Theta}(\theta_i)$ is the PDF of the scattering elevation angle $\theta_i$, and $f_{\Phi}(\phi_i)$ is the PDF of the scattering azimuth $\phi_i$, $f_{\Theta}(\theta_i)$ can be approximated by the normalized weighted phase functions of Rayleigh and Mie scattering [5]:

$$f_{\Theta}(\theta_i) = k_{\text{ray}}^{\text{ray}} + k_{\text{mie}}^{\text{mie}} \theta_i, \ 0 < \theta_i < \pi$$

(2)

where $k_{\text{ray}}$ and $k_{\text{mie}}$ are the atmospheric scattering coefficient, and $k_{\text{ray}}^{\text{ray}}$ and $k_{\text{mie}}^{\text{mie}}$ are the Rayleigh scattering and Mie scattering coefficients, respectively. $f_{\Theta}(\theta_i)$ and $f_{\Phi}(\phi_i)$ are the phase functions of Rayleigh scattering and Mie scattering, respectively, and the expressions are as follows [7]:

$$f_{\Theta}^{\text{ray}}(\theta_i) = \frac{3[1 + 3\gamma + (1 - \gamma)\cos^2 \theta_i]}{8(1 + 2\gamma)} \sin \theta_i$$

(3)

$$f_{\Theta}^{\text{mie}}(\theta_i) = \frac{1 - g^2}{2} \left[ \frac{1}{(1 + g^2 - 2g\cos \theta_i)^2} \right] \sin \theta_i$$

(4)

where $\gamma$, $g$ and $f$ are model parameters obtained from experiments. Ultraviolet photons have energy loss in the actual propagation process, which is mainly related to the transmission.
distance. When the photon energy is exhausted or the energy is not enough to be detected, we believe that the photon should be in a dissipated state at this time, and even if it is in the receiving field of view (FOV), it cannot reach the receiver [6]. The energy of the photon is expressed by introducing the survival probability $p_s$ in the MCS model.

When $i = 0$, $p_s = 1$, and the survival probability of a photon after $n^{th}$ order scattering is [1]:

$$p_{s,n} = p_{s,n-1} \times e^{-k_d d_n} (1 - f_d(\theta_n) \Omega_r)$$  \hspace{1cm} (5)

where $\Omega_r$ is the solid angle formed by $L_r$ and the receive aperture $A_r$. So the detection probability of a photon after $n^{th}$ order scattering can be approximated as:

$$f_d = \begin{cases} 
\frac{k_s}{k_e} e^{-k_d d_n} \cos \phi_r & \min(1, \frac{f_s(\theta_n) \Omega_r}{2\pi \sin \theta_n}), \text{ in FOV and } p_{s,n} \geq 0.1 \\
0 & \text{otherwise}
\end{cases}$$  \hspace{1cm} (6)

In the above formula, $\phi_r$ is the the angle between $u_r$ and $u_n$. We can judge whether photons are in the receiving field of view according to $\cos \phi_r$ and $\cos \beta_r$ [3], [8]. Therefore, the probability that a photon is emitted from the transmitting end and reaches the receiving end after $n^{th}$ order scattering is [6]:

$$P_n = \int \cdots \int_V p_d(\frac{k_s}{k_e})^{n-1} dQ_0 \cdots dQ_{n-2} dQ_{n-1}$$  \hspace{1cm} (7)

The above formula is a transcendental integral without a closed-form solution, so it can be calculated by introducing the MCI method and rewritten as [5]:

$$P_n = \int \cdots \int_V g_n(d, \theta, \phi) d\theta d\phi \prod_{i=0}^{n-1} \int f_d(d_i) f_s(\theta_i) f_\phi(\phi_i) dQ_i$$  \hspace{1cm} (8)

where $g_n(d, \theta, \phi) = p_d(\frac{k_s}{k_e})^{n-1} \prod_{i=0}^{n} f_d(d_i) f_s(\theta_i) f_\phi(\phi_i)$.

Selecting a sampling function in the integral space to satisfy $f_s(\theta, \phi) \neq 0$ and introducing an objective function $O_n^* = \frac{g_n(d, \theta, \phi)}{f_d(d, \theta, \phi)}$, formula (8) can be converted to:

$$P_n = \int \cdots \int_V O_n^* f_n d\theta d\phi \prod_{i=0}^{n-1} \int d\theta_i d\phi_i$$  \hspace{1cm} \begin{align} & = E(O_n^*) \end{align}  \hspace{1cm} (9)

The performance of the model varies according to the sampling function [1], [3]. The improved MCI-PIS model is still an important sampling of the photon moving distance and uniform sampling of the scattering elevation angle, and the sampling function is as follows [5] and [6]:

$$f_n = \prod_{i=0}^{n-1} [f_d(d_i) f_s(\phi_i)] \left(\frac{1}{\pi}\right)^{n-1} \frac{2}{\beta T}$$  \hspace{1cm} (10)

$N$ photons($x_1, x_2, \ldots, x_N$) are sampled in the scattering space $V$, and according to the law of large numbers, the probability of receiving a photon is [6] and [8]:

$$P_n = \lim_{N \to \infty} \frac{1}{N} \sum_{i=1}^{N} O_n^*(x_i)$$  \hspace{1cm} (11)

The path loss of UV multiple scattering is related to the reception probability. According to the calculation formula of UV multiple scattering path loss, the path loss $PL$ can be obtained as [5]:

$$PL = 10 \times \log_{10} \frac{1}{P_n}$$  \hspace{1cm} (12)

According to the order of receiving time from small to large, the receiving probability of photons is arranged to obtain a receiving probability sequence $\{P_{n,T_1}, P_{n,T_2}, \ldots, P_{n,T_N}\}$. And the pulse response of UV light multiple scattering can be obtained by normalizing the sequence with the receiving time interval and receiving aperture $A_r$ [1], [8].

### III. SIMULATION RESULTS AND ANALYSIS

In order to verify the correctness of the improved model and analyze the model performance under different system parameters under clear atmospheric conditions, some of the simulation parameters are used with typical atmospheric sparsity and model coefficients, which are given by [2] and [5]. The specific parameters are shown in Table 1.
TABLE 1. Some simulation parameters.

| Symbol | Value       | Quantity       |
|--------|-------------|----------------|
| $A_r$  | $1.77 \times 10^{-4}$ | Receive Aperture |
| $k_{\text{aq}}$ | $0.802 \times 10^{-3}$ | Atmospheric Absorption Coefficient |
| $k_{\text{ray}}$ | $0.266 \times 10^{-3}$ | Rayleigh Scattering Coefficient |
| $k_{\text{mie}}$ | $0.284 \times 10^{-3}$ | Mie Scattering Coefficient |
| $\gamma$ | 0.017 |                |
| $f$    | 0.72       |                |
| $g$    | 0.5        |                |

A. PATH LOSS

We simulate the path loss of the two models under different system parameters such as communication distance, transceiver elevation angle, transceiver azimuth, and transceiver divergence angle, and the results are shown in Figure 2, Figure 3 and Figure 4. We can observe that under different parameters, the path loss curves calculated by the two models are consistent, and the path loss of the improved model is always higher than that of MCI-PIS because of considering the photon survival probability, which indicates that the improved model is correct for calculating the path loss of ultraviolet multiple scattering.

![Figure 3](image1.png)  
![Figure 4](image2.png)

**FIGURE 3.** The path loss of the two models:(a) $\phi_T$, (b) $\phi_R$.

**FIGURE 4.** The path loss of the two models:(a) $\beta_T$, (b) $\beta_R$.

From Figure 2, we can observe that the path loss increases with the increase of distance, but decreases while transceiver elevation angle increases. (a) shows that when the distance increases from 10 to 20, the path loss increases fastest, and after it increases to 80, the path loss increases slowly, which shows that the path loss is less sensitive to distance in the case of long distance communication. And it can be seen from (b) that the path loss is almost the same when transceiver elevation angle ranges from $70^\circ$ to $90^\circ$. Therefore, we can conclude that when the transceiver of the ultraviolet communication system works in the x-o-y plane, it is allowed to deviate from the x-o-y plane by plus or minus $20^\circ$ in the z-axis direction.

Figure 3 shows the effect of the azimuth angles of the two models on the path loss performance. It should be noted that the x-axis of the transmit azimuth angle should be a negative value, because only in this way the transmitter is deflected toward the receiver. When the azimuth angle does not exceed $40^\circ$, the performance of the improved model and the MCI-PIS model is quite different, and the path loss is not sensitive to the change of the azimuth angle. However, beyond $40^\circ$, the path loss is the same for both, and decreases sharply with increasing angle. Thus, we can draw a conclusion that the azimuth angle is the most sensitive system parameter.
parameter for path loss. Therefore, in order to obtain better system performance, the azimuth angle should be set to 90° as much as possible, which is equivalent to that the two ends of the UV communication need to be on one axis.

The effect of divergence angle on path loss is shown in Figure 4. The path loss of the improved model is 0.3 dB higher than that of MCI-PIS model on the system parameter of the divergence angle. Combining Figure 4(a) and (b), we can find that the transmit divergence angle and receive divergence angle affect the path loss in different ways. Specifically, the path loss increases as the transmit divergence angle increases, and decreases as the receive divergence angle increases. In addition, when the angle changes from 0° to 90°, the path loss caused by the change of the transmitter divergence angle
fluctuates within 3 dB, while the effect of the receiver divergence angle on the path loss is as high as 7 dB, which leads to the conclusion that the path loss is more sensitive to the change of the receiver divergence angle. Therefore, we can say that the reasonable setting of the receiving divergence angle is more important to the performance of the ultraviolet optical communication system.

**B. IMPULSE RESPONSE**

Ultraviolet light communication will cause serious pulse broadening due to the way of scattering and propagation. In order to improve the reliability of communication, the influence of pulse broadening should be avoided as much as possible. Therefore, we simulated the system impulse response performance under different parameters of the two models, and the results are shown in Figure 5, Figure 6 and Figure 7 respectively.

The impulse response performance of the two models is shown in Figure 5 (a), (b) and (c) respectively, and we can observe that the impulse response performance of the two models is almost the same under the same system parameters. Besides, we can find that when the distance increases, the impulse response shows a trend of decreasing intensity and increasing width. However, when the transceiver elevation and azimuth increase, the opposite results that the impulse response shows a trend of increasing intensity and narrowing width are obtained, and the results of specific changes are shown in Figure 6(a), (b) and (c) respectively. Here we only simulate the impulse width of the improved model.

From Figure 6, we can see that the effects of range, elevation and divergence angles on impulse width are linear, while the effects on impulse intensity are exponential. Among them, the effect of distance on the impulse response is minimal.

When the distance is 100 m, the width does not exceed 6 μs which is about 5 times that when the distance is 10 m, and the intensity is $1.2 \times 10^{-4}$ W/m² which is about 2% of that when the distance is 10 m. In addition, it is worth noting that when the elevation angle exceeds 40°, the pulse width transformation is relatively gentle, and the variation range does not exceed 1 μs, which also proves the conclusion in Section 3.1 that the elevation angle of the ultraviolet optical communication system changes within a certain range, and its performance is hardly affected.

Then, we simulated the effects of the transmit divergence angle and receive divergence angle on the impulse responses of the two models respectively, and the results are shown in Figure 7, where (a) and (b) are the performance comparisons of the two models, (c) and (d) are the variations in the impulse response of the improved model. From (a) and (b), we can know that the performance of the two models on the impulse response is almost the same under the same divergence angle. In Figures (c) and (d), we observe that the impulse width changes with the increase of the divergence angle without a trend, but the variation ranges are small, which are in the two intervals of (2.8, 4.2) μs and (2.8, 3.8) μs, respectively. However, the change of impulse intensity has a trend, in which the effect of divergence angle on pulse intensity decreases exponentially, while the effect of receiving divergence angle increases exponentially.
C. THE EFFICIENCY

The computational efficiency of the two models can be expressed by the running time of the program. The computer used in the simulation in this paper is configured with an 11th-generation Intel CPU and a RAM of 16G, and the operation time of the two models is shown in Figure 8.

We can see that the improved model is more computationally efficient than MCI-PIS as the scattering order increases. When the scattering order \( n = 6 \), the speed of the improved model is 18 times faster than that of MCI-PIS, which is about 1.26 times that of MCI-PIS. In addition, when the number of simulated photons increases, the calculation time of the two models increases tenfold. When the number of photons \( N = 10^6 \), the calculation time of the two models is hundreds of seconds, and when the number of photons \( N = 5 \times 10^6 \), the computation time of the two models is in the order of thousand seconds, and the computational efficiency of the improved model is about 1.16 times that of MCI-PIS. Therefore, we can conclude that the improved model has about 20% improvement over the MCI-PIS model in terms of computational efficiency. When encountering severe haze or sandy atmospheres where UV photons experience more than 6th order scattering or when encountering situations where a large number of photons are considered, calculations with the improved model can greatly reduce time and improve efficiency.

IV. CONCLUSION

We analyzed the improved MCI-PIS model of UV multiple scattering, compared the performance of the improved model and the original MCI-PIS model, and analyzed UV multiple scattering. The results are divided into three parts: path loss, impulse response and efficiency. The simulation results show that the improved model has almost the same path loss and impulse response performance as the MCI-PIS model within a certain numerical range, but the computational efficiency is about 1.2 times that of the MCI-PIS model. In addition, the simulation results also show that the azimuth angle is the system parameter that affects the path loss performance the most, and the elevation and azimuth angles have a greater impact on the impulse response.

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