Research Article

Analysis of Visible Light Communication Link's Performance in Fire Smoke Environment

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Received 9 April 2021; Accepted 20 May 2021; Published 26 May 2021

Academic Editor: Heng Liu

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This paper mainly studies the communication performance of visible light communication link in fire smoke environment. Compared with the previous studies, this study no longer only considers a single wavelength and considers the influence of smoke and background light noise. Firstly, the variation of background light noise caused by sunlight during a day was analyzed, then signal-to-noise ratio (SNR) and bit error rate (BER) of the visible light communication link in fire smoke environment with different visibility were calculated, and finally, the variation of received power with the angle β between the LED optical axis and the communication link (from LED to receiver) was analyzed. The results show that, during a day from 07:00 to 18:30, background light noise first increases and then decreases, BER changes in the same trend and reaches the maximum at about 13:00, while SNR changes in the opposite trend and reaches the minimum at about 13:00. When visibility is 100 m, the maximum difference of SNR between 7:00 and 13:00 is about 19 dB, and the maximum difference of BER is about $5.3E-10$. At 7:00, the maximum difference of SNR is about 13 dB between the visibility of 1 m and the visibility of 100 m, and the maximum difference of BER is about $1.44E-11$, and received power decreases with the increase of β . In addition, SNR increases with visibility of fire smoke environment, and BER changes in the opposite trend. Lastly, in order to enhance the performance of visible light communication in fire smoke environment, this paper gives the transmitting power scheme.

1. Introduction

Currently, the application of visible light communication (VLC) is becoming more and more widespread. The new visible light communication technology based on LED has many advantages: it can meet high-speed communication while realizing lighting, is harmless to human eye health and does not cause radiation damage to the human body, is not easily subject to electromagnetic interference, and has good confidentiality. In addition, VLC technology also does not require radio spectrum certification, which can effectively solve the problem of spectrum limitation of radio frequency (RF) technology [1] and can also be used for indoor target localization. Therefore, this technology is playing an increasingly important role in vehicle networking, underground mines, and other fields.

Although visible light communication has many advantages, it is easily affected by the atmospheric environment [2], and indoor fire smoke and outdoor fire smoke are one of the most important factors. Due to the short light wavelength and serious light scattering, the visible light communication link is easily blocked. In addition, the outdoor rain, fog, snow, and background light noise are also important factors to interfere with the visible light communication link. In order to improve the performance of visible light communication in a special environment, it is necessary to study the transmission characteristic of the visible light communication link in this environment. In 2013, Zhu et al. [3] studied the effect of smoke on free-space optical (FSO) communication and proposed that the attenuation coefficient decreases exponentially as the volume of the shell increases. In 2016, Chen et al. [4] studied the

transmittance of laser at different wavelengths in smoke. In a 4.8 m flue, the transmittance of 10.6 μm laser is twice that of 1.06 μm laser when the smoke concentration is less than 1.0947 g/m^3 . In the same year, it was also concluded that, in a 400 m flue, the transmittance of 10.6 μm laser is up to 104 times that of 1.06 μm laser [5]. In the same year, Wang and Duan [6] proposed that, in different concentrations of smoke environment, due to the absorption of the laser beam by suspended particles, the laser is attenuated in the process of transmission. In 2019, Jiang and Song [7] proposed that the FMCW laser ranging system is attenuated and absorbed by smoke particles when measuring the echo signal in smoke environment, and this leads to the result that it is difficult to extract effective signals.

However, the above literature studies mainly studied lasers with a certain wavelength, and current research related to visible light communication is less likely to consider environmental factors. There are even fewer research and reports on the communication performance of visible light in fire smoke environment. In this paper, we focus on analyzing the performance of visible light communication link in fire smoke environment and provide a theoretical basis for the application of visible light communication in this environment in the future.

2. Analysis of Background Light Noise

The background light noise P_{bg} cannot be ignored in visible light communication in fire smoke environment, and the blackbody radiation model can be used to describe spectral radiance $W(\lambda, T_B)$ [8, 9]:

$$W(\lambda, T_B) = \frac{2\pi h_p c^2}{\lambda^5} \left[\frac{1}{e^{(h_p c / \lambda k T_B)} - 1} \right], \quad (1)$$

where h_p is Planck's constant, c is the speed of light, λ is the wavelength, k is Boltzmann's constant, and T_B is the average surface temperature of the sun, usually taken as 6000 K.

The global solar irradiance E_{global} has a wavelength range between 0.3 μm and 4.0 μm , and it serves as the input for global spectral irradiance measurements. The peak spectral irradiance S_{peak} is given by [8]

$$S_{\text{peak}} = 0.0001 E_{\text{global}}^2 + 1.5768 E_{\text{global}}. \quad (2)$$

The global solar irradiance W_{approx} can be derived as [8]

$$W_{\text{approx}}(\lambda) = S_{\text{peak}} \frac{W(\lambda, 6000)}{\max[W(\lambda, 6000)]}. \quad (3)$$

The spectral range of the receiver E_{det} is given by [9]

$$E_{\text{det}}(\lambda) = \int_{\lambda_1}^{\lambda_2} W_{\text{approx}}(\lambda) d\lambda, \quad (4)$$

where λ_1 and λ_2 are the boundary values of the optical bandpass filter, and P_{bg} can be obtained as follows [9]:

$$P_{bg} = E_{\text{det}} T_0 A n^2, \quad (5)$$

where T_0 is the peak filter transmission coefficient, which can reach 1, A is the area at the receiving side, and n is the internal refractive index.

Based on the measured global solar irradiance, the trend of P_{bg} during a day can be derived as shown in Figure 1.

As can be seen from Figure 1, before 13:00, with the sun rising, P_{bg} increases from -3 dBm (7:00) to 16 dBm (13:00). After 13:00, with the sun falling, P_{bg} decreases to 3 dBm at 18:30, and from the above analysis, it is found that P_{bg} changes obviously during a day. Therefore, the influence of background light noise on the performance of visible light communication in fire smoke environment cannot be ignored, and the background light noise caused by sunlight is usually Gaussian white noise, which can be removed by using denoising.

3. SNR and BER of Visible Light Communication in Fire Smoke Environment

According to the Lambert-Beer law, when the transmission distance is D , the received power P_r is determined by the attenuation coefficient. The visibility (V) is obtained from Koschmieder's law [10]:

$$V = \frac{10 \log_{10}(T_{\text{th}})}{\beta_k} \text{ (km)}, \quad (6)$$

where T_{th} is the visual threshold, which usually takes 2%.

The relationship between the attenuation coefficient β_k and V can be approximated as

$$V \text{ (km)} = \frac{10 \log_{10}(T_{\text{th}})}{\beta_k} \left(\frac{\lambda}{\lambda_0} \right)^{-q}, \quad (7)$$

where λ_0 is the maximum spectral value in the solar band. For the visible wavelength band, it is derived that

$$\beta_k = \int_{380}^{780} \frac{10 \log_{10}(T_{\text{th}})}{V} \left(\frac{\lambda}{\lambda_0} \right)^{-q} d\lambda. \quad (8)$$

The coefficient q depends on the experimental data such as the size and distribution of the particles [11]:

$$q = \begin{cases} 1.6, & V > 50 \text{ km} \\ 1.3, & 6 \text{ km} < V < 50 \text{ km} \\ 0.16V + 0.34, & 1 \text{ km} < V < 6 \text{ km} \\ V - 0.5, & 0.5 \text{ km} < V < 1 \text{ km} \\ 0, & V < 0.5 \text{ km} \end{cases} \quad (9)$$

Then P_r can be obtained as follows:

$$P_r = \frac{A_R}{\pi \theta^2 L^2} P_t e^{-(\beta_k D)}, \quad (10)$$

where A_R is the received range, θ is the beam divergence angle, D is the transmission distance, and P_t is the emitted power of the LED. β_k is the attenuation coefficient ($A_R = 10 \text{ cm}$, $\theta = 60^\circ$, and $D = 10 \text{ m}$).

SNR can be used as a measure of visible light communication's performance, and SNR can be expressed as the relationship between received power and environmental noise, as follows [12]:

FIGURE 1: Variation of background light noise during daytime.

$$\text{SNR} = \frac{R^2 P_r^2}{\sigma_{\text{shot}}^2 + \sigma_{\text{thermal}}^2}, \quad (11)$$

where R is the photoresponsivity of the photodetector at the receiver, σ_{shot}^2 is the scattering noise variance, and $\sigma_{\text{thermal}}^2$ is the thermal noise variance.

$$\sigma_{\text{shot}}^2 = 2qRP_rB + 2qRP_{bg}I_2B, \quad (12)$$

where q is electric charge, B is noise bandwidth, and I_2 is noise bandwidth current [12].

$$\sigma_{\text{thermal}}^2 = \frac{8\pi kT_k}{G} \eta A I_2 B^2 + \frac{16\pi^2 kT_k \Gamma}{g_m} \eta^2 A^2 I_3 B^3, \quad (13)$$

where k is the Boltzmann constant, T_k is the absolute temperature, η is the capacity per unit area, A is the area at the receiver side, Γ is the FET channel noise factor, G is the open-loop voltage gain, g_m is the FET transconductance, and I_3 is the bandwidth coefficient of noise as a percentage of the full ascending cosine.

Using OOK optical intensity modulation, BER can be obtained as follows:

$$\text{BER} = Q(\sqrt{\text{SNR}}),$$

$$Q(x) = \frac{1}{2\pi} \int_x^\infty e^{((-y^2)/2)} dy. \quad (14)$$

Select the LED with 45 mW emission power; when the background light noise is maximum, the following is P_r in different visibility environment.

As can be seen from Figure 2, P_r increases with an increase in visibility. P_r increases from 0.0122 mW ($V=1$ m) to 0.01302 mW ($V=12$ m) and increases by 6.7% and finally converges to a constant value of about 0.01302 mW.

The literature [13] gave the smoke attenuation coefficient at different wavelengths, and we took the wavelength of 670 nm for the calculation and compared it with the measured results in that literature. Figure 3 shows the

FIGURE 2: Received power in different visibility.

FIGURE 3: Comparison of the measured value and the theoretical value of the attenuation coefficient.

comparison between the measured and theoretically calculated values of the attenuation coefficient.

As can be seen from Figure 3, the calculated value of attenuation coefficient is basically consistent with the measured value, and the relative error is about 0.07%. Here only the influence of smoke particles and background light noise factors is considered, while the complexity of the actual measurement environment is not only influenced by these two factors but also by the measured attenuation coefficient which is often larger than the theoretical attenuation coefficients. To avoid this problem, sunny weather should be chosen for the actual measurement.

Figures 4 and 5 show the variation of SNR and BER during a day in fire smoke environment with different visibility.

By analyzing Figures 4 and 5, it can be seen that SNR first decreases and then increases, and BER first increases and then decreases during a day. Before 13:00, continuously SNR

FIGURE 4: SNR for a day in fire smoke environment with different visibility.

FIGURE 5: BER for a day in fire smoke environment with different visibility.

decreases and BER increases, and finally, SNR reaches the minimum and BER reaches the maximum during a day. After 13:00, SNR increases and BER decreases. In addition, it can be concluded that SNR increases and BER decreases with the increase of visibility.

The visible light communication system can be used to adjust P_t to cope with the fire smoke environment. When V is 12 m and D is 10 m, P_r is calculated to be about 0.013 mW. In order to make the receiving power reach 0.013 mW at any time, P_t can be adjusted according to the real-time visibility.

As shown in Figure 6, when P_r is always 0.013 mW, the power of the LED transmitter is adjusted with visibility.

From Figure 6, it can be seen that, in fire smoke environment, when V is less than 0.02 km, the less visibility, the more P_t is required, when V is more than 0.02 km, P_t tends to a constant value and is almost no longer affected by visibility. At this time, the transmitter can adjust the value of P_t according to different visibility, so that P_r is always 0.013 mW.

4. Path Loss and Power Loss in Fire Smoke Environment

Figure 7 shows a simple visible light communication scene in fire smoke environment. The visible light communication link's performance in fire smoke environment is not only affected by the background light noise but also by the absorption of smoke particles.

As can be seen from Figure 7, the distance between the receiving side and the LED is D , the radius of the detector at the receiving side is r , the angle between the communication link and the normal of the receiving side is α , the angle of the communication link to the axis of the LED light beam is β , Ω_r is the solid angle of the detector's receiving field of view, and the receiving area is A . The relationship between them satisfies the following equation [12]:

$$A \cos \alpha \approx D^2 \Omega_r. \quad (15)$$

In the device manual of LED, the axial light intensity I_0 is usually given, and we can obtain the total luminous flux at the transmitter F_s [12]:

$$F_s = \int_0^{\Omega_{\max}} I_0 g_s(\theta) d\Omega = \int_0^{\theta_{\max}} 2\pi g_s(\theta) \sin \theta d\theta, \quad (16)$$

where $g_s(\theta)$ is the spatial distribution function of the LED lamp and $\Omega_{\max}$ is the stereo angle of the LED beam, which is related to the maximum half-angle of the beam as follows:

$$\Omega_{\max} = 2\pi(1 - \cos \theta_{\max}). \quad (17)$$

We can get the total luminous flux at the receiving end F_r [14]:

$$F_r = I_0 g_s(\beta) \Omega_r. \quad (18)$$

The LED can be viewed as a Lambertian source, and its spatial distribution function is $g_s(\theta) = \cos^m(\theta)$. The Lambert radiation coefficient m can be obtained by $m = (-\ln 2)/\ln(\cos \phi_{1/2})$ where $\phi_{1/2}$ is the radiation half-angle of the LED, and let $\theta_{\max} = \pi/2$, the path loss L_L can be derived by integrating.

$$L_L = \frac{F_r}{F_s} = \frac{I_0 g_s(\beta) \Omega_r}{I_0 \int_0^{\theta_{\max}} 2\pi g_s(\theta) \sin \theta d\theta} = \frac{g_s(\beta) A \cos \alpha}{D^2 \int_0^{\theta_{\max}} 2\pi g_s(\theta) \sin \theta d\theta},$$

$$L_L \approx \frac{(m+1)A}{2\pi D^2} \cos \alpha \cos^m(\beta). \quad (19)$$

In addition, the power loss L_P can be expressed as

FIGURE 6: Variation of emitted power with visibility.

FIGURE 7: Visible light communication scene in fire smoke environment.

$$L_p = \frac{S_r(\lambda)}{S_s(\lambda)}, \quad (20)$$

where $S_s(\lambda)$ is the power spectral density of the light source and $S_r(\lambda)$ is the power spectral density of the receiving side.

According to equation (19), it can be derived that

$$F = 683 \cdot \int_{380\text{nm}}^{780\text{nm}} S(\lambda) V(\lambda) d\lambda. \quad (21)$$

It is known that when the visual acuity function is consistent, $L_p = L_L$.

LED parameter tables usually give F_s or I_0 of LED, $g_s(\theta)$, and the normalized power spectral density $S'_s(\lambda)$. When F_s and I_0 are interchangeable, $S_s(\lambda)$ can be found from $S_s(\lambda) = C S'_s(\lambda)$, where C is the conversion factor, which can be derived from equation (16) [14]:

$$C = \frac{F_s}{683 \times \int_{\lambda_{sL}}^{\lambda_{sH}} S'_s(\lambda) V(\lambda) d\lambda}, \quad (22)$$

where λ_{sL} and λ_{sH} are two endpoint values of the wavelength range of the visible band, respectively, and $S_r(\lambda)$ can be obtained by the following formula:

$$S_r(\lambda) = L_p S_s(\lambda) = C L_p S'_s(\lambda). \quad (23)$$

An optical filter with the spectral response of $R_f(\lambda)$ is added to the photodetector, and P_r is expressed as follows:

$$P_r = \int_{\lambda_{rL}}^{\lambda_{rH}} S_r(\lambda) R_f(\lambda) d\lambda, \quad (24)$$

where λ_{rL} and λ_{rH} are two end values of the optical filter [14].

The normalized radiation power spectral density waveforms and visible light filter waveforms are shown in Figures 8 and 9.

As can be seen from Figure 8, there are two peaks in the normalized radiation power spectrum density of the LED, which are distributed at 450 nm and 560 nm. LED is a white LED with yellow phosphor on a blue substrate, blue LED itself does not have a very high luminous flux, but after adding the yellow phosphor, the excitation energy is 8 times higher than the original. So this LED is more suitable for visible light communication. As can be seen from Figure 9, the filter has a filter range of 380 nm–780 nm, which only allows all wavelengths of visible light to pass through, effectively filtering out the nonvisible band of the spectrum.

β is calculated to be constantly changing, when background light noise is maximum, and Figure 10 shows the relationship between P_r and β in fire smoke environment.

As can be seen from Figure 10, P_r is gradually decreasing with the increase in β . When the LED beam axis coincides

FIGURE 8: Normalized power spectral density of LEDs.

FIGURE 9: Visible light filter.

FIGURE 10: Variation of received optical power with angle β .

TABLE 1: Parameter table.

Parameter	Numerical
P_t	45 mW
A	1 cm ²
I_0	1100 cd
N	1.5
R	0.53 A/W
T_k	298°C
G	10
g_m	30 ms
Γ	1.5
H	112 pf/cm ²
I_2	0.562 A
I_3	0.0868 A
B	2 MHz

with the communication link, P_r can reach its maximum. So in order to improve the communication efficiency of the visible light communication system, it should try to make the LED light axis coincide with the communication link.

5. Conclusion

This paper investigates the factors that affect the performance of visible light communication in fire smoke environment. By analyzing the change rule of background light noise during a day, the changing relationship between SNR/BER and visibility during a day and the influence of β was obtained. It is concluded that, with the enhancement of external light, SNR keeps decreasing, BER keeps increasing, and the communication performance decreases. In addition, the received power decreases with the increase in β .

Through the above study, it is concluded that the effects of fire smoke and background light noise on visible light communication performance cannot be ignored, and it is crucial to improve the performance of LED transmitting equipment and the performance of photoelectric detection equipment at the receiving side. For the transmitter side, the paper gives the corresponding transmitting power according to different visibility, and the adjustment scheme can be applied in the actual fire smoke environment. For the receiver side, in practical applications, the filter can reduce the effect of background light noise by increasing the modulation frequency. Meanwhile, β should be minimized. In the next research work, the above scheme will be applied in practice, and in the complex fire environment, the automatic power regulation device is used to verify the above scheme.

Table 1 shows the parameters used in this paper.

Data Availability

The data used to support the findings of this study are obtained from previous studies [9, 10, 12].

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this article.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (61405157), the National Natural Science Foundation (2019JQ-901), and the Key Industry Innovation Chain Project of Shaanxi Province (2017ZDCXL-GY-06-01).

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