30 Gbps visible light communication in rainy environments based on laser diodes

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Rain has a strong attenuation effect on light, which can impact the performance of visible light communication (VLC). In this paper, we addressed the crucial challenge of implementing high-speed VLC systems in rainy environments by focusing on the performance of different wavelengths under varying rain conditions. By analyzing the attenuation characteristics of four laser diodes at different wavelengths under various artificial rain environments, we developed a high-speed VLC system optimized for rainy channel high-speed visible light communication by employing the orthogonal frequency-division multiplexing modulation scheme. By integrating channel-adaptive pre-equalization and bit-loading algorithms, our system optimized signal transmission in rainy channels, enabling an aggregated data rate exceeding 30 Gbps, which was the highest reported data rate for VLC in rainy channels, to the best of our knowledge.

Keywords: visible light communication; attenuation of rainy channel; adaptive orthogonal frequency-division multiplexing modulation algorithm.
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1. Introduction

Wireless communication in rainy environments is crucial for applications like vehicular communication, where reliable and high-speed data transmission is essential for safety and efficiency. Traditional radio-frequency (RF) communication is confronted with significant challenges in such environments due to limited spectrum resources and susceptibility to weather-related interference. Visible light communication (VLC) is a promising technology for next-generation mobile communication (6G) that offers unique advantages, including high speed and less susceptibility to electromagnetic interference[1,2]. Although VLC is typically used in indoor environments, these advantages have led to growing interest in its application in outdoor environments, particularly in vehicular communication[3]. In outdoor VLC scenarios, free-space optical (FSO) communication systems based on lasers for VLC face challenges under adverse weather conditions such as rain, snow, and fog[4,5].

Recent studies have shown that rain-induced interference significantly impacts the signal-to-noise ratio (SNR), bit error rate (BER), and data rate in VLC systems, leading to a sharp decline in performance under adverse weather conditions[6–8]. Simulations indicate that as rainfall intensity increases, the absorption and scattering properties of rainwater reduce received signal strength, which raises the BER and negatively affects communication effectiveness[9]. Most existing studies focus on theoretical simulations of VLC channel characteristics, which lack experimental validation. Elamassie *et al.*[6] conducted vehicle-to-vehicle communication (V2V) channel modeling to quantify rain and fog effects on VLC, simulating the maximum achievable transmission distance under various conditions. Ariatama *et al.*[7] employed the Marshall-Palmer model for rain channel simulations, using an on-off keying-non-return-to-zero (OOK-NRZ) modulated red light emitting diode (LED)-based V2V-VLC system, achieving a maximum data rate of 10.547 Gbps in light rain (0.125 cm/h). In contrast, experimental studies typically achieved a relatively low data rate, such as those by Danys *et al.*[8], who used commercial automotive LED tail lights in an artificial rain environment with a 5-m transmission distance. They achieved a 6 Mbps data rate using up to 64-QAM modulation under a rainfall intensity of 8.8 mm/h, but this falls short of the high speed required for outdoor VLC applications[11–15]. In contrast, laser diode (LD)-based wavelength division multiplexing (WDM) VLC in free space can achieve a high data rate. For instance, some studies exploring the WDM VLC demonstrate the potential for using multiple wavelength channels to achieve higher capacity and robustness in various communication environments. Wei *et al.*[10] developed a bidirectional over 20 Gbps VLC communication system that supports signal remodulation based on tricolor R/G/B LDs, and then they employed polarization multiplexing to realize a higher speed VLC system with a record data rate of 40.665 Gbps[11]. Therefore, the current WDM laser communication rates in rainy environments are significantly lower compared to those in free-space conditions, highlighting the need for further improvement.

In this paper, we developed a high-speed VLC system employing orthogonal frequency-division multiplexing (OFDM) modulation in an artificial rain environment. First, we measured the transmission characteristics of visible light lasers with wavelengths of 405, 450, 520, and 650 nm in a rainy channel. Subsequently, we transmitted optical signals using four high-modulation bandwidth lasers to achieve high data rates. A 3.38-m-long rain chamber and a rain generator were used to simulate outdoor rainy conditions in the laboratory. The results indicate that the communication rate attenuation of visible light in a rainy environment is influenced by wavelength, with longer wavelengths experiencing less attenuation than shorter wavelengths under heavy rain conditions. This demonstrates the advantage of optical communication in rainy environments, whereas longer wavelengths can maintain higher data rates despite increased path loss. Specifically, using a 650 nm LD, the maximum data rate of 8.01 Gbps was achieved under a path loss of 3.6 dB in light rain conditions, and a data rate of 7.40 Gbps was maintained even when the path loss increased to 4.9 dB, with a forward error correction (FEC) limit of less than 3.8×10^{-3}. The system demonstrated an aggregated data rate exceeding 30 Gbps.

2. Methods and Experiments

Rain causes attenuation of optical signals, subsequently affecting communication rates and distances[17]. Absorption and scattering are the two primary factors leading to this attenuation[18]. The optical power attenuation characteristics in the rainy environment channel can be described by the Beer–Lambert law[16,19],

$$\text{Path loss} = 10\ \lg \frac{P_t}{P_r}, \tag{1}$$

where P_t and P_r represent the transmitted and received optical power, respectively. The path loss is related to the size of raindrops, the wavelength of the laser, and the transmission distance in the rainy channel.

Accurate channel research is crucial for achieving optimal communication performance in experiments. Previous research has primarily focused on theoretical simulations, often lacking consideration of real conditions[6,7]. To more accurately evaluate the relationship between rain droplet attenuation and wavelength in visible light, we tested the transmission characteristics of different wavelength lasers in a 3.38-m artificial rain environment, as shown in Fig. 1. The artificial rain in the laser link was simulated using a rain generator, with droplet diameters ranging from 0.5 mm for light rain to 2 mm for heavy rain. Water from a pump was delivered through a hose with a diameter of 5 cm, with nozzles placed every 30 cm to maintain a uniform flow, thereby simulating even rainfall. The rain intensity amount was adjusted by controlling the water flow, and precise measurements were taken using a standard graduated cylinder with a minimum division value of 0.1 ml. Rainwater was collected at five different positions in the rain chamber for 2 min to determine the total rainfall, and the average value was taken to reduce measurement errors and calculate the rainfall intensity (mm/h). A light-power meter (Thorlabs PM100D) was used to measure the optical power at the transmitter and receiver ends under various rainfall conditions, and path loss was calculated.

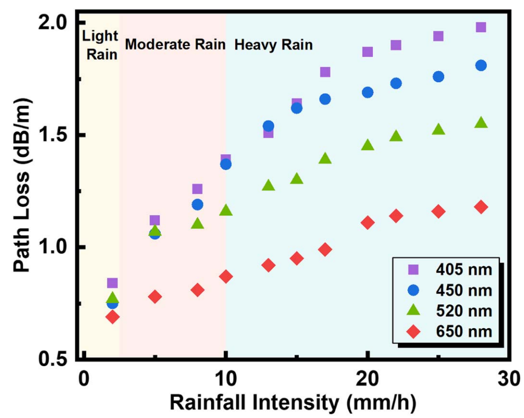

Fig. 1. Path loss with changes in rainfall intensity measured at wavelengths of 405, 450, 520, and 650 nm in the visible light range based on LDs: light rain (<2.5 mm/h), moderate rain (2.5–10 mm/h), and heavy rain (10–30 mm/h).

As shown in Fig. 1, within the visible light wavelength range, path loss is increased with shorter wavelengths of the LDs in the rainy environment. This can be explained by Mie scattering[20], which occurs when the size of scattering particles is larger than the wavelength of the incident light. Given that the diameters of rain droplets are generally much larger than the wavelengths of visible light, Mie scattering plays a dominant role in the attenuation of light. The intensity of Mie scattering is inversely proportional to the square of the wavelength, meaning that shorter wavelengths scatter more intensely than longer wavelengths. This results in higher attenuation for shorter wavelengths because they experience greater scattering. Additionally, as rainfall intensity increases, the size of the rain droplets grows, further amplifying the scattering effect. It is important to note that although longer wavelengths in the infrared range (such as 1550 nm) have lower path loss in rainy environments, in the existing outdoor vehicular traffic systems, infrared communication systems lack existing equipment and require additional installations, whereas VLC can be directly integrated into existing infrastructure such as vehicle headlights and street lights, making it easier to implement. Additionally, the VLC systems offer distinct advantages in terms of cost, equipment availability, and dual functionality for both communication and illumination. Therefore, we believe that the VLC system is more suitable for achieving high-speed communication in rainy environments.

Meanwhile, rainfall can also cause laser beam wandering and scintillation, leading to fluctuations in the received signal strength and frequency shift, further degrading the quality of the received signal and impacting the data rate[21,22]. To mitigate these effects, the WDM VLC system can compensate for the fluctuations caused by beam wandering and scintillation, allowing for higher overall data rates and more reliable performance even under challenging weather conditions[23]. In order to compare and study the communication performance of different wavelengths in the visible light range under rainy environments, we set up 405, 450, 520, and 650 nm LD-based high-speed VLC systems.

The schematic diagram and photograph of the VLC system in the artificial rain channel are shown in Fig. 2. First, OFDM digital signal data were generated offline using MATLAB, and then the signal was fed into an arbitrary waveform generator (AWG, Keysight M8190A) to be converted into an analog signal for output. This output signal was amplified by a preamplifier (Amp, Mini-Circuits ZHL-42W+, 4.2 GHz) with a gain of 38 dB, and then a direct current (DC) bias was added using a bias-tee (Mini-Circuits ZFBT-6GW+, 6 GHz) to keep the signal positive. The combined signal was then used to drive the semiconductor laser, which was packaged with a collimating lens. The collimated visible light signal was transmitted through a 3.38-m artificial rain chamber and focused by a lens at the receiver end onto a P-I-N photodiode (PIN) (Femto, 1.4 GHz), converting the received optical signal into an electrical signal. This PIN photodiode has a high responsivity in the visible light spectrum, ensuring high SNR of the attenuated signal through the rain channel. Finally, a high-speed digital signal analyzer (DSA, Agilent DSA90604A Infiniium, 20 GS/s) was used to capture the output signal from the PIN and transfer it back to MATLAB for offline demodulation and analysis.

To address the significant signal attenuation in rainy environments, this study utilized a high spectral efficiency OFDM modulation scheme to enhance the transmission rate. Pre-equalization and bit-loading techniques were employed to optimize the modulation and demodulation processes, thereby increasing the overall channel capacity. The modulation process began with the generation of a large binary data sequence, which was then mapped to different quadrature amplitude modulation (QAM) formats after serial-to-parallel conversion. The QAM order was determined by the estimated frequency response of each OFDM subcarrier, which varied across different frequencies[24]. Typically, high-frequency subcarriers suffered from lower SNR, and the bit-loading algorithm was used to optimize channel utilization by accounting for this nonuniform SNR distribution. The pre-equalization algorithm further enhanced performance by adjusting the signal power to compensate for high-frequency fading, with adaptive coefficients tuned to the specific channel conditions[25]. Once the signal was modulated, it underwent 2× upsampling, followed by Hermitian symmetry enforcement and an inverse fast Fourier transform (IFFT) to convert the signal into its real-valued form. A cyclic prefix (CP) was then added to the signal to mitigate intersymbol interference (ISI). During demodulation, the received signal was processed through CP removal, fast Fourier transform (FFT), downsampling, channel estimation, QAM demapping, and parallel-to-serial conversion to retrieve the binary data[26]. MATLAB was used to compute BERs, SNRs, constellation diagrams, and an average spectral efficiency to determine the data rate[27].

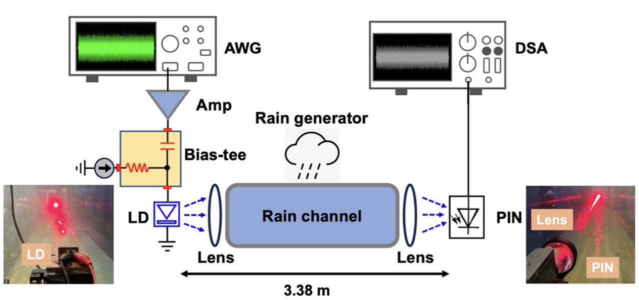

Fig. 2. Experimental setup (including the transmitter side, channel, and receiver side) and process diagram of a VLC system based on a laser in the rainy environment channel of 3.38 m.

3. Results and Discussion

The characteristics of the 405, 450, 520, and 650 nm LDs are shown in Fig. 3(a). In the experiment, the optimal operation with the highest SNR was identified by adjusting the voltage and current of the device for communication. In addition, the −3 dB modulation bandwidths of the four LDs were tested by the network analyzer (VNA, PicoVNA 106), which are 2.1, 2.8, 2.4, and 2.2 GHz, respectively, as shown in Fig. 3(b). The high bandwidth of the LDs accommodates high-frequency OFDM signals up to 2 GHz, thereby enabling higher transmission rates. Under these conditions, we optimized the pre-equalization and bit-loading for different rainy environments to improve SNR and spectral efficiency, thereby achieving larger channel capacity.

To achieve maximum VLC data transmission rate in the rainy environment channel, we first selected the 650 nm LD as the transmitter for communication tests based on the path loss tests and analysis mentioned above, and the rainfall conditions were varied with no rain, light rain (2.5 mm/h), moderate rain (10 mm/h), and heavy rain (21 mm/h) in a 3.38-m artificial rain chamber. To ensure the accuracy and consistency of the test results, the system's optical path setup was kept unchanged during the experiment. The power spectrum of the OFDM signals after pre-equalization under each condition is shown in Fig. 4. Despite variations in rainfall intensity affecting the laser path loss and thus the received signal optical power, the optimized pre-equalization could maintain relatively similar signal power spectra for different conditions. Even under heavy rain, the

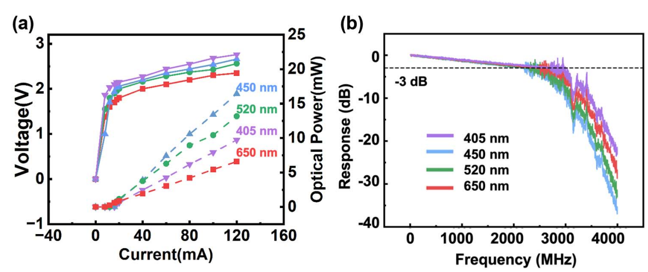

Fig. 3. (a) The I-V and P-I curves of four wavelength lasers. (b) The −3 dB bandwidths of four wavelength lasers.

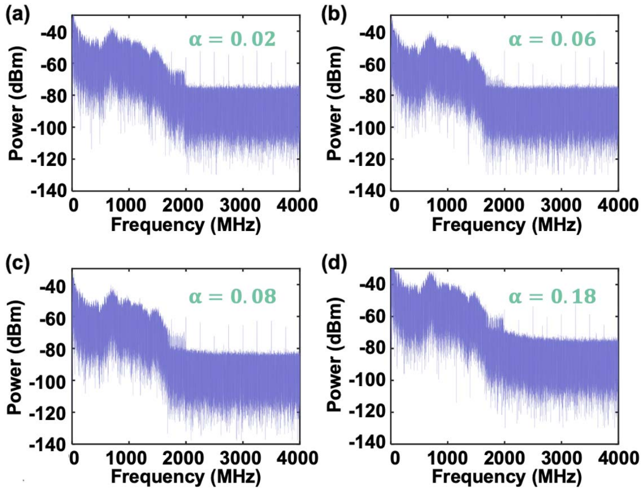

Fig. 4. The frequency spectrum using adaptive pre-equalization coefficient in different channel environments at (a) free space, (b) light rainfall, (c) moderate rainfall, and (d) heavy rainfall.

signal power spectrum shows improvement despite increased path loss, indicating that pre-equalization effectively enhances spectral efficiency and data rate.

Figure 5 shows the SNR and bit loading across subcarrier frequencies. As rainfall increases, the system's average SNR gradually decreases, with values of 18.34, 17.18, 15.45, and 14.71 dB under the four conditions, respectively. The corresponding spectral efficiencies are 4.4104, 4.0045, 3.8814, and 3.6974 bps/Hz, respectively. Through adaptive adjustment of the SNR gap for different channels, data rates can be optimized to enhance performance. Additionally, high-frequency signal attenuation became more pronounced with increased rainfall, as high-frequency signals were more sensitive to path loss than low-frequency signals. Therefore, it is necessary to increase the pre-equalization coefficient to counteract high-frequency attenuation, as shown in Fig. 4. This highlights the importance

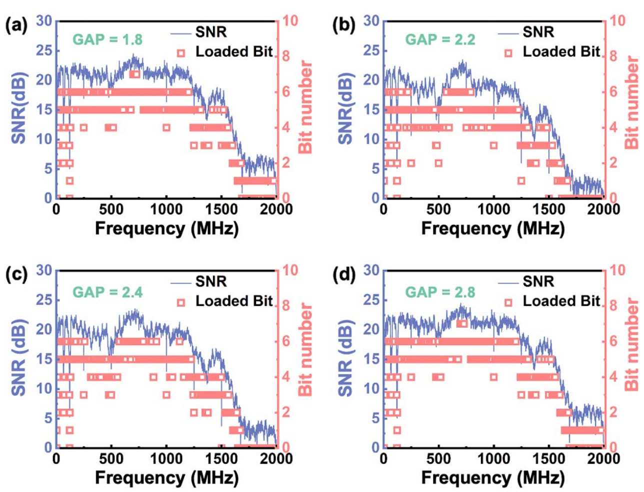

Fig. 5. SNR and bit numbers based on the adaptive OFDM bit-loading algorithm using different SNR gaps in different channel environments at (a) free space, (b) light rainfall, (c) moderate rainfall, and (d) heavy rainfall.

of the pre-equalization algorithm in high-speed VLC systems under rainy conditions, as it better improves the high-frequency response. The highest data rate curves below the FEC limit for the four channels are shown in Fig. 6(d), with maximum data rates of 8.82, 8.01, 7.76, and 7.40 Gbps, respectively. The trends in transmission rate and path loss are consistent; that is, as the rainfall increases, the path loss rises but gets more gradual, and so does the decrease in transmission rate.

After evaluating the communication performance of the 650 nm LD in a rainy environment, we extended our experiments to examine the impact of laser wavelength on communication by testing 405, 450, and 520 nm LDs. To ensure a fair comparison and eliminate any influence of varying laser performance on communication, we controlled the emission power of each laser to be consistent across all experiments and applied the same 2 GHz bandwidth OFDM signal. The maximum data rates below the FEC limit for the four wavelengths are summarized in Table 1, and the corresponding data rates versus BER are

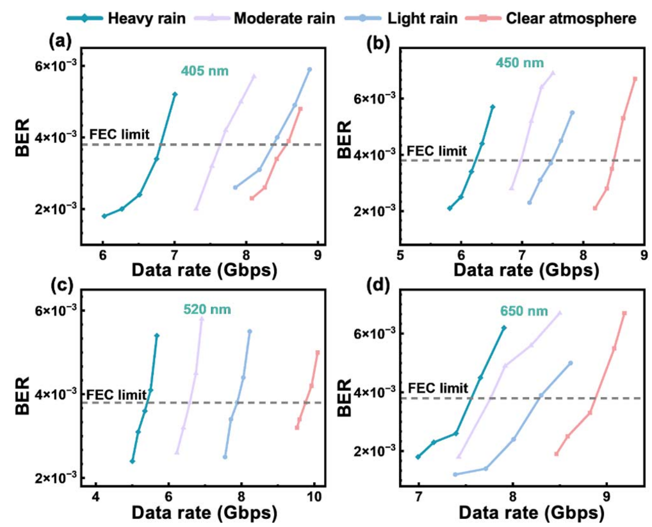

Fig. 6. BERs and data rates of various wavelength LDs in free space, heavy, moderate, and light rainfall conditions at (a) 405, (b) 450, (c) 520, and (d) 650 nm.

Table 1. Summary of Data Rates (Gbps) for Different Wavelengths in Different Rainy Environments.

Wavelength (nm)	0	2.5 mm/h rainfall	10 mm/h rainfall	21 mm/h rainfall
405	8.42	7.61	7.32	5.91
450	8.47	7.48	6.98	6.17
520	8.76	7.88	6.58	5.35
650	8.82	8.01	7.76	7.40
Aggregated data rate (Gbps)	34.47	30.98	28.64	24.83

illustrated in Fig. 6. The results indicate that under light rain conditions, the data rates decreased by 9.7%, 11.9%, 13.8%, and 9.2% for 405, 450, 520, and 650 nm lasers, respectively, showing a relatively uniform decline. However, under heavier rain conditions, the rate decreases by 29.9%, 27.2%, 38.9%, and 16.2% for the corresponding wavelengths.

It is clear that the 650 nm laser consistently outperformed the others, particularly in heavy rain, which can be attributed to the lower optical power loss and higher modulation bandwidth of the red LD. This aligns with the path loss trends presented in Fig. 1, where longer wavelengths such as 650 nm exhibit lower path loss, reinforcing the importance of wavelength selection in optimizing communication performance under adverse weather conditions. By aggregating the data rates across all tested wavelengths and considering their optimal performance under varying rain conditions, the system demonstrated a theoretical aggregated data rate exceeding 30 Gbps in light rain channels.

4. Conclusion

In summary, we systematically tested the path loss and communication performance of various wavelength lasers within the visible light range in different rainy environment channels for high-speed wireless communication. The results indicated that the attenuation of data rates in the rainy environment is influenced by the wavelength. The 650 nm LD exhibited the weakest attenuation, achieving a maximum data rate of 8.01 Gbps with a path loss of 3.6 dB in light rain conditions. Even under heavy rain conditions, when the path loss increased to 4.9 dB, the data rate remained at 7.40 Gbps. These findings suggest that the 650 nm laser offers a particularly advantageous balance between communication performance and path loss, making it well-suited for high-speed communication applications. Furthermore, the potential integration of multiple lasers with varying wavelengths and power levels could establish the foundation for future systems that combine white-light illumination with communication capabilities, enhancing the versatility and utility of VLC technology in outdoor V2V scenarios.

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