Design and Implementation of an SDR-Based VLC Transceiver Using Red Laser and Bias-Tee for Analog Signal Transmission

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ABSTRACT

Software Defined Visible Light Communication (SDVLC) enables flexible and reconfigurable optical wireless communication through software-defined signal processing. This paper presents the design and implementation of an SDR-based VLC transceiver using a 650 nm red laser diode and bias-tee-based optical interfacing for analog signal transmission. The platform was validated by transmitting Amplitude Modulation (AM) and Frequency Modulation (FM) signals using two HackRF One SDR devices integrated with GNU Radio at a 10 MHz carrier frequency. The optical front-end comprises a red laser diode transmitter and a BPW34 photodiode receiver. Experiments were conducted indoors and outdoors under varying transmission distances and ambient lighting conditions. Successful analog optical transmission was achieved for both modulation schemes. FM outperformed AM, achieving an average Signal-to-Noise Ratio (SNR) of 76.50 dB versus 45.53 dB while showing greater robustness against optical attenuation and ambient light interference. The measured bandwidths were approximately 17 kHz for AM and 19 kHz for FM. Reliable communication was achieved over distances up to 9 m indoors and 6 m outdoors using a low-cost 6 mm, 5 mW red laser diode. These results verify the proposed SDR-based VLC transceiver for analog signal transmission, with FM providing superior performance.

Keywords
VLC, SDR, AM, FM, Bias-Tee

1. INTRODUCTION

Visible Light Communication (VLC) is increasingly attractive as a wireless communication technique because it can utilize many unlicensed frequencies, is immune to electromagnetic interference, and has inherent security at the physical layer. VLC is a promising candidate for high-capacity short-range wireless links for future communication systems beyond 5G and 6G. It is particularly useful in scenarios where traditional radio-frequency communication experiences spectrum congestion or interference (1–4).

Much of the recent VLC research has focused on high-speed transmission systems using laser diodes, advanced photonic devices, and complex digital modulation techniques. The strong transmission and modulation ability of laser diode transmitters enables high-speed VLC links to carry very large amounts of data, making them good candidates for future optical wireless networks (5–9). At the same time, several studies have explored the application of software-defined approaches for VLC, and they frequently utilize Software Defined Radio (SDR) platforms. These platforms offer flexible options for the creation of signals, their processing, and rapid development and testing of new systems (10–17). These techniques offer greater flexibility in experiments than communication systems that depend on specific hardware.

Among available SDR platforms (18–20), HackRF One has emerged as an attractive platform for communication research due to its wide frequency coverage and compatibility with GNU Radio. Previous studies have investigated RF-to-optical and optical-to-RF signal conversion using HackRF-based VLC architectures (21,22), while bias-tee circuits have also been proposed as practical solutions for combining RF and DC components in optical communication systems (23). However, most existing SDR-based VLC studies focus on digital communication systems, high-speed transmission techniques, or optical conversion architectures. Although analog modulation techniques have been extensively studied in communication systems (24,25), their implementation and experimental evaluation in SDR-based VLC transceivers remain relatively limited.

Furthermore, comparative studies of analog modulation schemes in SDR-based VLC environments remain limited. In particular, the performance of AM and FM at varying

transmission distances and ambient illumination conditions has not been thoroughly investigated, despite their distinct sensitivity to amplitude variations and channel impairments. Since optical wireless channels are prone to path loss, alignment constraints, and ambient-light interference, a systematic evaluation of AM and FM in an SDR-based VLC environment is therefore necessary.

As part of the broader SDVLC project, this paper presents the design and implementation of an SDR-based analog VLC transceiver using HackRF One and GNU Radio, a 650 nm red laser diode, a BPW34 photodiode, and bias-tee-based optical interfacing. AM and FM modulation schemes are implemented at a carrier frequency of 10 MHz and evaluated experimentally under indoor and outdoor conditions with varying transmission distances and illumination levels.

2. RESEARCH METHOD

2.1 Design and Realization

2.1.1 System Overview

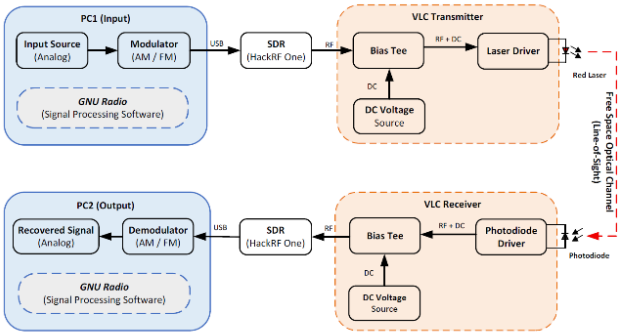


Figure 1. illustrates the block diagram of the proposed VLC system.

As illustrated in Figure 1, the system consists of a transmitter, a free-space optical channel, and a receiver, each implemented using two HackRF One SDR devices running GNU Radio. At the transmitter, the analog input signal is modulated using AM or FM at a carrier frequency of 10 MHz and delivered to the laser diode via a Bias-Tee circuit. At the receiver, the BPW34 photodiode detects the optical signal, which is extracted by a second Bias-Tee circuit and demodulated in GNU Radio to reconstruct the transmitted information.

2.1.2 Selection of Light and Light Sensor

A 650 nm red laser diode was selected as the optical transmitter due to its narrow beam divergence, high optical power concentration, and spectral compatibility with the BPW34 photodiode, making it well-suited for line-of-sight VLC transmission.

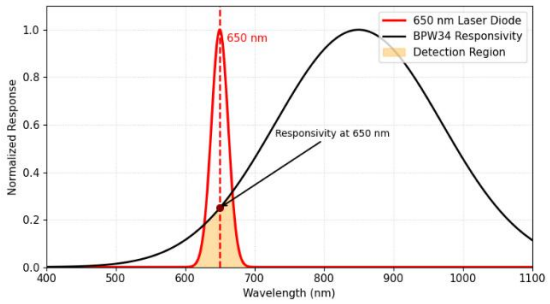


Figure 2. Spectral compatibility between the 650 nm red laser diode and the BPW34 photodiode.

As shown in Figure 2, the 650 nm emission falls within the peak responsivity region of the BPW34 photodiode, which was reverse-biased to enhance detection speed and sensitivity.

2.1.3 Optical Link Based on Laser, Photodiode, and Bias-Tee

A Bias-Tee circuit was employed to combine the 10 MHz RF signal and the DC bias required by the laser diode, as shown in Figure 3.

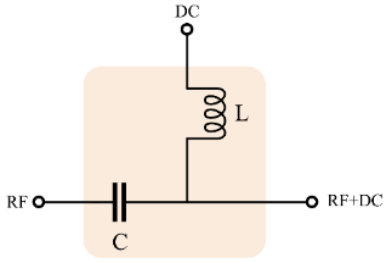


Figure 3. Bias-Tee Circuit Design.

The circuit comprises a coupling capacitor and a shunt inductor, with component values determined from their respective reactance relationships. The coupling capacitor was selected to provide sufficient reactance at 10 MHz, ensuring efficient RF signal coupling, as expressed in (1).

$$C = \frac{1}{2\pi f X_C} \quad (1)$$

where:

- C is the capacitance (F),
- X_C is the capacitive reactance (Ω), and
- f is the operating frequency (Hz).

The inductor was chosen to present high reactance at the operating frequency, blocking RF leakage into the DC bias path, as expressed in (2).

$$L = \frac{X_L}{2\pi f} \quad (2)$$

where:

- L is the inductance (H),
- X_L is the inductive reactance (Ω), and
- f is the operating frequency (Hz).

2.1.4 Optical Link Interfacing with SDR

As illustrated in Figure 4, the HackRF One SDR interfaces with the optical link via Bias-Tee circuits on both the transmitter and receiver sides. On the transmitter side, the Bias-Tee combines the RF output from the SDR with the DC bias required to drive the laser diode, enabling intensity-modulated optical transmission. On the receiver side, a second Bias-Tee extracts the RF component from the photodiode output and routes it back to the HackRF One SDR for demodulation in GNU Radio.

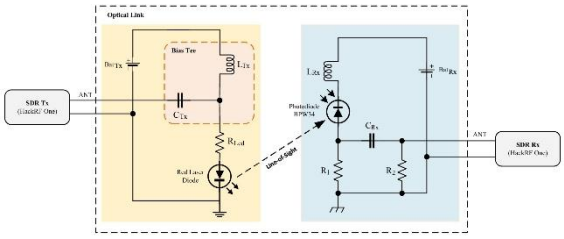


Figure 4. Interfacing architecture between the HackRF One SDR and the proposed VLC optical link.

2.1.5 Analog AM/FM Transceiver Using Optical Link and SDR

The entire analog VLC transceiver architecture using GNU Radio, HackRF One SDR, and the optical link is shown in Figure 5. GNU Radio utilizes either AM or FM to generate and modulate sinusoidal test tones and WAV audio signals, which are then sent via the SDR and optical channel. The optical wave is transformed into an electrical signal at the receiver, recorded by the SDR, and then demodulated in GNU Radio to obtain the original data. This design provides an adaptable testbed for assessing analog modulation techniques over the VLC channel.

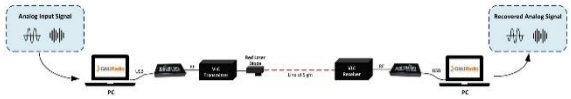


Figure 5. Analog AM/FM VLC transceiver architecture using GNU Radio, HackRF One SDR, and the proposed optical link.

2.1.6 AM and FM Modulation Implementation on Transceiver

Figure 6 shows that the AM transmitter was implemented in GNU Radio using HackRF One SDR operating at a carrier frequency of 10 MHz. The transmitter supports two input sources: sinusoidal test tones and WAV audio signals, selected via a configurable signal path. The generated analog signal is processed and transmitted through the SDR platform for subsequent optical conversion by the VLC transmitter. This configuration enables both controlled frequency-response measurements and real-audio transmission experiments.

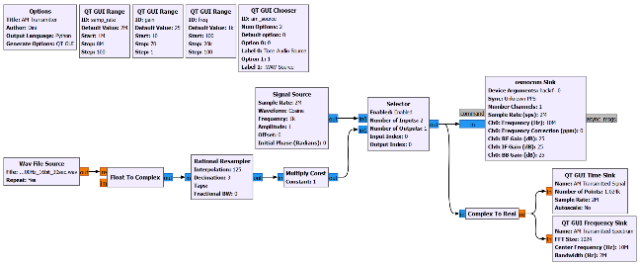


Figure 6. GNU Radio implementation of the AM transmitter using HackRF One SDR.

The AM receiver was implemented in GNU Radio to recover the transmitted information from the optical waveform received. The signal acquired by HackRF One is demodulated to reconstruct the original analog information, and the recovered output can be monitored in both the time and frequency domains for performance evaluation, as shown in Figure 7.

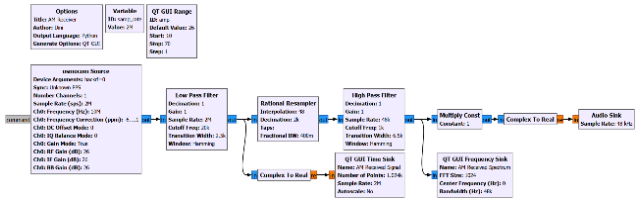


Figure 7. GNU Radio implementation of the AM receiver using HackRF One SDR.

Figure 8 shows that the FM transmitter accepts analog audio input from either a sinusoidal tone generator or a WAV file source and performs frequency modulation using the GNU Radio WBFM Transmit block, which provides integrated modulation processing and built-in audio pre-emphasis. The modulated signal is subsequently transmitted through the HackRF One SDR at a 10 MHz carrier frequency.

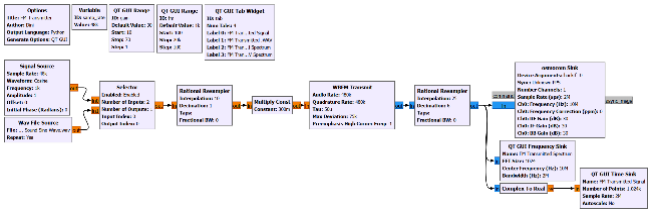


Figure 8. GNU Radio flowgraph of the proposed FM transmitter implemented using HackRF One SDR.

The FM receiver acquires the incoming signal via HackRF One and demodulates it using the GNU Radio WBFM Receive block. The recovered audio is resampled and directed to the audio output for performance evaluation, as shown in Figure 9.

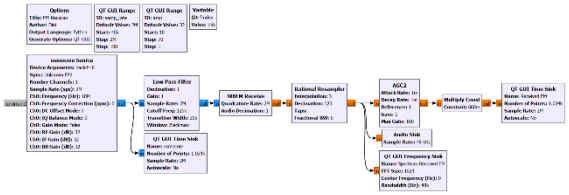


Figure 9. GNU Radio flowgraph of the proposed FM receiver implemented using HackRF One SDR.

2.2 Experimental Testing

2.2.1 Test Signals and Evaluation Metrics

The experiments were performed using two types of analog input signals: sinusoidal test tones from 100 Hz to 20 kHz (for frequency response evaluation) and WAV audio signals (for practical transmission assessment). System performance was evaluated in terms of SNR, THD, dynamic range, and receiver sensitivity, as summarized in Table 1

Table 1. Technical Specifications for Analog Transmission

No	Input Signal	Description
1	Sinusoidal Test Tone	100 Hz – 20 kHz
2	WAV Audio	Audio file (.wav)

2.2.2 Experimental Setup

(a)

(b)

Figure 10. Experimental configurations of the proposed VLC transceiver under: (a) indoor and (b) outdoor conditions.

The experimental setup comprised two dedicated computers, each connected to a HackRF One device serving as the transmitter and receiver, respectively. The optical units were mounted on tripods to maintain stable line-of-sight alignment throughout the measurements, as shown in Figure 10.

2.2.3 Indoor Testing Scenario

Indoor experiments were conducted under normal room lighting in a line-of-sight configuration. The transmitter–receiver distance was varied in steps to investigate the effect of propagation distance on signal quality.

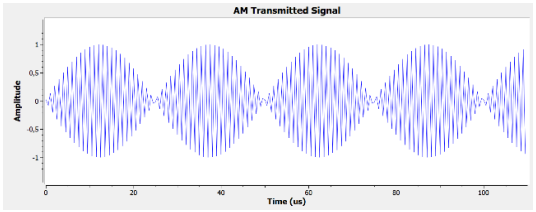
2.2.4 Outdoor Testing Scenario

Outdoor experiments were carried out under direct ambient-light exposure in a line-of-sight configuration. The effect of ambient light on the transmission performance was evaluated by measuring at two illumination levels of about 5,000 lux and 50,000 lux. The distance between the transmitter and receiver was increased in steps, and the performance was noted for both the AM and FM modulation at each distance.

3. RESULTS

3.1 AM Transceiver Signal Characteristics

Figure 11 shows the AM transceiver time domain and frequency domain characteristics. The received signal maintains the sinusoidal shape of the transmitted signal, verifying successful signal recovery through the optical link. The dominant spectral component at the transmitted frequency is clearly visible in the frequency domain, confirming the correct AM modulation and demodulation.



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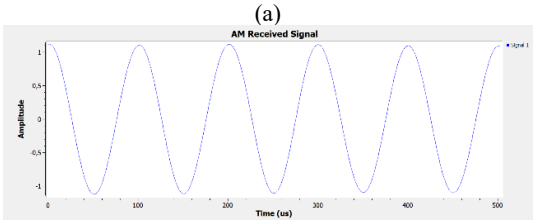

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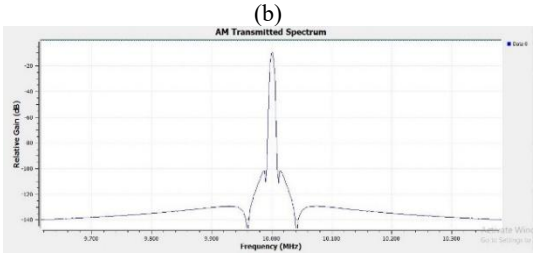

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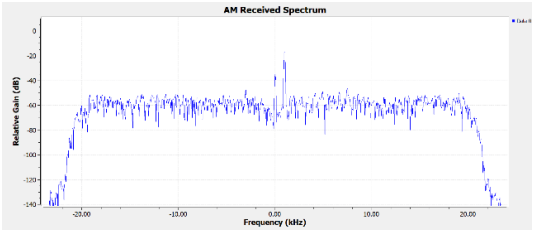
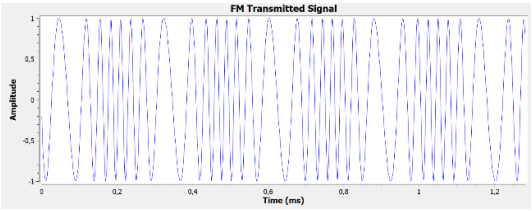


(d)

Figure 11. Time-domain and frequency-domain characteristics of the AM transceiver: (a) transmitted signal waveform, (b) received signal waveform, (c) transmitted signal spectrum, and (d) received signal spectrum.

3.2 FM Transceiver Signal Characteristics



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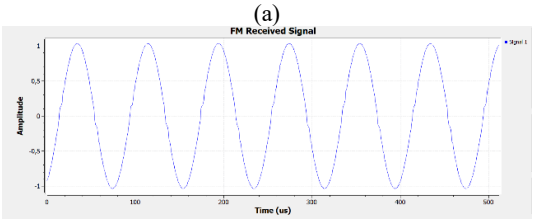

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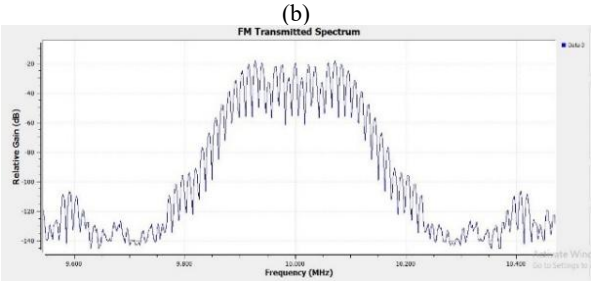

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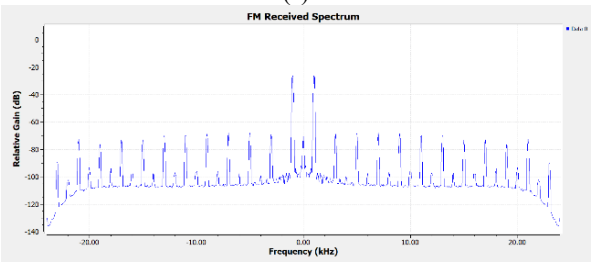


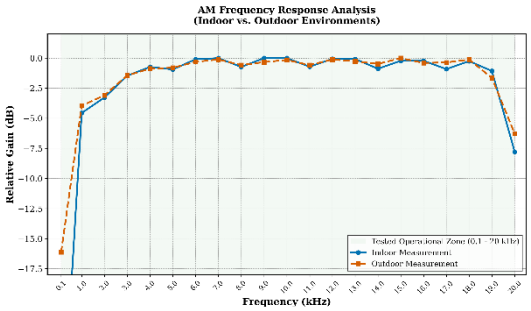
(d)

Figure 12. Time-domain and frequency-domain characteristics of the FM transceiver: (a) transmitted signal waveform, (b) received signal waveform, (c) transmitted signal spectrum, and (d) received signal spectrum.

The time-domain and frequency-domain characteristics of the FM transceiver are shown in Figure 12. The recovered signal has a stable waveform and frequency content matching that of the transmitted signal. The broader transmitted spectrum is characteristic of FM modulation, while the spectrum at the receiver verifies the successful recovery of the signal over the optical VLC link.

3.3 Frequency Response Evaluation

As shown in Figure 13, the normalized frequency response of both AM and FM transceivers was evaluated from 100 Hz to 20 kHz under indoor and outdoor conditions. The AM response is relatively flat in the mid-frequency region with attenuation at the lower and upper limits, yielding an effective bandwidth of approximately 16.8–17.1 kHz based on the −3 dB criterion. The FM response exhibits better gain flatness and remains close to the reference level up to 19 kHz, with minimal variation between indoor and outdoor measurements.



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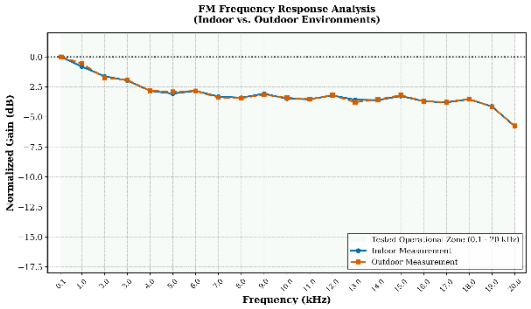
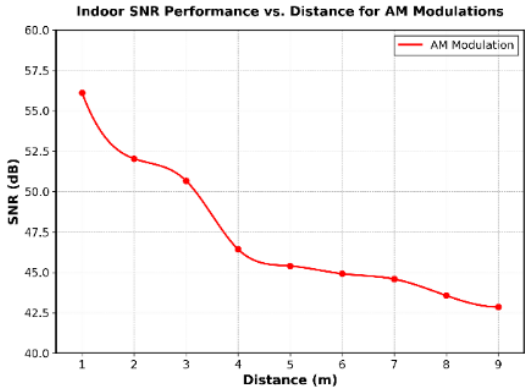


(b)

Figure 13. Normalized frequency response of the proposed VLC transceiver under indoor and outdoor conditions: (a) AM modulation, (b) FM modulation.

3.4 Indoor Performance of AM and FM Modulation



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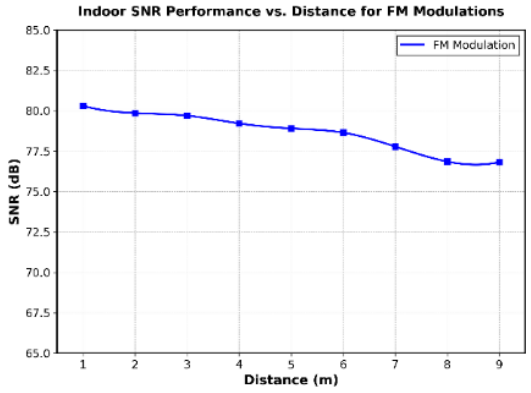
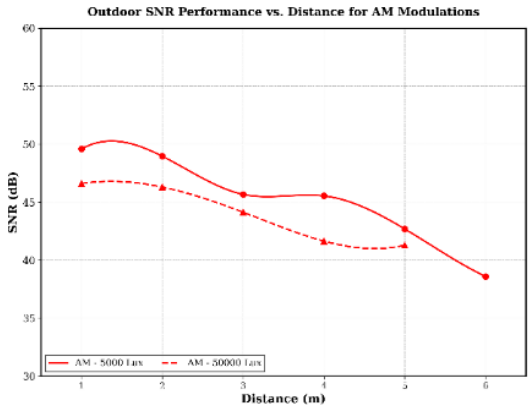


(b)

Figure 14. Indoor SNR performance under variable transmission distances: (a) AM modulation, (b) FM modulation.

Figure 14 shows the indoor SNR performance for different transmission distances. For both modulation schemes, the SNR decreases with distance due to the optical path loss and the decrease of received optical power. FM has higher SNR consistently, with SNR values above 76.83 dB in the evaluated range, while AM decreases from 56.12 dB to 42.86 dB. These results confirm the better robustness of FM against optical attenuation in indoor VLC environments.

3.5 Outdoor Performance of AM and FM Modulation



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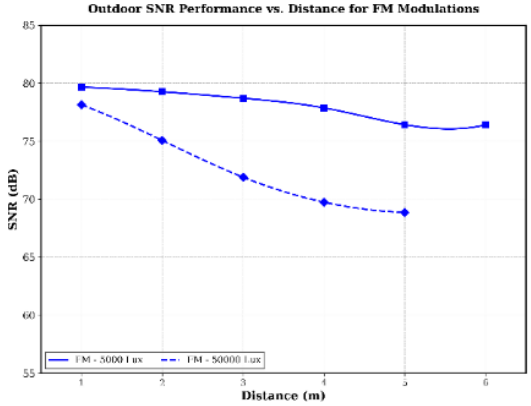

(b)

Figure 15. Outdoor SNR performance under variable transmission distances and ambient-light conditions: (a) AM modulation, (b) FM modulation.

Figure 15(a) shows the outdoor SNR trend of the AM transceiver for two ambient lighting scenarios. As the transmission distance increases, the SNR gradually degrades at both illumination levels, and the degradation is more severe under 50,000 lux because of the increased background optical interference. This behavior shows how AM is sensitive to changes in ambient light.

The outdoor SNR performance of the FM transceiver is shown in Figure 15(b). Higher illumination levels result in lower received SNR, but FM is relatively stable in the range of distance evaluated. The smaller variation of SNR with respect to AM confirms the higher robustness of FM against ambient light interference and the optical-channel disturbances.

3.6 Overall Performance Summary

Table 2 summarizes the overall performance of the proposed VLC transceiver over modulation schemes and environmental conditions. Compared to AM, FM always shows better SNR and dynamic range, with less distortion, and is more resistant to optical attenuation and interference from ambient light.

Table 2. Overall System Experimental Results

Modulation Type	SNR (dB)	THD (%)	Dynamic Range	Enviromental Conditions
AM	47.4	0.61	49.10	Indoor (192 lux)
	45.18	3.4	41.63	Outdoor (5,000 lux)
	44	5.5	40.71	Outdoor (50,000 lux)
FM	78.68	1.57	68.01	Indoor (192 lux)
	78.06	1.7	67.83	Outdoor (5,000 lux)
	72.74	1.62	63.01	Outdoor (50,000 lux)

4. DISCUSSION

4.1 Effect of Distance and Ambient Illumination

With the increase in transmission distance, the SNR will gradually degrade due to the optical path loss and the received optical power. Experiments outdoors show more degradation due to the ambient solar illumination, which increases the system noise floor. Under high illumination conditions (50,000 lux), we observed more severe optical interference, which mainly affected the AM transmission.

4.2 Performance Evaluation

FM always performed better than AM over all the experimental conditions, with an average of 76.50 dB SNR against 45.53 dB for AM. FM has a higher SNR due to its inherent immunity to optical attenuation and ambient light

interference, as the transmitted information is in the form of frequency variation instead of signal amplitude. Both modulation techniques were capable of successfully transmitting audio in the 100 Hz–20 kHz range. However, FM exhibited a more stable behavior for different distances and illumination levels. The implementation is limited by the transmission range, the requirement of strict line-of-sight alignment, and the susceptibility to strong ambient illumination.

4.3 Comparison with Existing Works

Table 3 shows the proposed VLC transceiver significantly outperforms the previously reported HackRF-based VLC implementations in SNR. Prior works have focused on digital modulation schemes or RF-only SDR architectures. The proposed system can perform analog AM/FM transmission over an optical VLC link and demonstrate stable operation in indoor and outdoor environments.

Table 3. Performance Evaluation of AM and FM-Based VLC

Work	Modulation	Optical Source	Result
(22)	FM	RF Channel	SNR≥39 dB, THD≤2%
This Work	AM, FM	Red Laser, Bias-Tee	SNR 76.50 dB, THD 1.63% for FM, SNR 45.53 dB, THD 3.17% for AM

4.4 Potential Applications

Although the proposed VLC system was evaluated using analog AM and FM modulation, the developed SDR-based platform provides a flexible testbed for broader optical wireless communication research. Potential applications include short-range indoor wireless audio transmission, laboratory-scale optical communication experiments, education and training in SDR-based VLC systems. Furthermore, the modular architecture based on GNU Radio and HackRF One enables the implementation of additional analog and digital modulation schemes without requiring significant hardware modifications. This flexibility makes the proposed system a suitable Software-Defined Visible Light Communication (SDVLC) platform for evaluating and prototyping various optical wireless communication techniques, including LiFi, IoT, and hybrid RF/VLC networks.

5. CONCLUSION

This paper described the implementation of an analog visible light communication (VLC) transceiver based on software-defined radio (SDR) using HackRF One, GNU Radio, a 650 nm red laser diode, a BPW34 photodiode, and bias-tee based optical interfacing. The experimental results verified the successful analog signal transmission over the information bandwidth of 100 Hz-20 kHz at the carrier frequency of 10 MHz under both indoor and outdoor conditions. The performance evaluations indicated that FM outperformed AM in all cases with an average SNR of 76.50 dB over 45.53 dB for AM and showed higher transmission stability and better robustness to ambient optical interference. The obtained results show that FM gives better results for analog VLC transmission in the experimental conditions studied. In addition, the system was implemented using HackRF One SDR devices and GNU Radio, which provides a flexible platform for the processing of analog signals. Future work will include the implementation of digital modulation schemes and the inclusion of other performance metrics, such as BER and throughput analysis.

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