

VISIBLE LIGHT COMMUNICATION (VLC): COMMUNICATION USING VISIBLE LIGHT

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ABSTRACT

The growing number of wireless devices and increasing traffic density place a significant strain on the radio-frequency spectrum. Traditional communication channels – such as Wi-Fi and Bluetooth – face bandwidth limitations and are susceptible to interference. Against this backdrop, Visible Light Communication (VLC) technology emerges as a compelling alternative: it leverages LED lighting infrastructure for data transmission, without competing for radio-frequency resources. VLC technology provides additional, high-capacity communication channels and creates new opportunities for establishing secure, high-speed networks within indoor environments and for various specialized applications. VLC is a non-fiber-optic data transmission technology based on the use of visible light. A key motivation for this technology is that light can simultaneously serve the purposes of illumination, communication, and/or positioning. Consequently, this multifunctionality eliminates the need for an additional power source for data transmission or location tracking. The transition from legacy light sources to light-emitting diodes (LEDs) can be integrated with VLC technology. This article examines the operating principles of VLC, technical approaches, advantages, limitations, current challenges, and potential solutions. It also presents results from computer simulations and mathematical models of VLC systems.

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Introduction

The growing number of wireless devices and increasing traffic density place a significant strain on the radio-frequency (RF) spectrum. Visible Light Communication (VLC) technology [1, 2, 11] opens up additional, high-capacity communication channels and creates new opportunities for developing secure, high-speed networks for indoor environments and various specialized applications [2, 3].

The system operates within the visible portion of the spectrum, spanning from 400 THz ($\lambda \approx 750$ nm) to 790 THz ($\lambda \approx 380$ nm), as illustrated in Fig. 1. As shown, visible light represents only a small fraction of the entire optical spectrum (which also encompasses infrared and ultraviolet). In this context, modulation and demodulation are performed directly – bypassing the need for radio frequencies – which makes optical transmission systems significantly simpler than their RF-based counterparts. Furthermore, visible light remains the most accessible segment of the optical spectrum, largely due to the development of affordable technology.

Light-emitting diodes (LEDs) were invented in the 1960s. Over the course of just a few decades, they have evolved from single-color to multi-color, from low-brightness to high-brightness, and from short-lived to long-lasting components. Brightness has increased twentyfold every decade, while costs have dropped to just 1% of their original price. However, the concept of VLC was proposed only about two decades ago by Japanese scientists, who suggested that information could be encoded into a light source by having it flicker rapidly in accordance with the data being transmitted [1-3].

Fortunately, this flickering is imperceptible to the human eye, provided the frequency is at least 200 Hz. This allows for the seamless integration of VLC-capable LEDs with standard lighting LEDs [7, 9]. The first VLC standard, known as LiFi (Light Fidelity), was introduced as recently as 2011 [8, 14].

Since its inception, the VLC concept has evolved significantly; by 2019, data transmission speeds had exceeded 15 Gbps. Specifically, a data rate of 15.73 Gbps was reported over a 1.6-meter link using OFDMA as an access scheme, with standard off-the-shelf LEDs [10, 13]. Furthermore, it has been reported that connections with speeds exceeding 6.5 Gbps and 1.5 Gbps can be maintained at distances of 10 meters and 20 meters, respectively.

Despite the numerous advantages of VLC – as outlined in the introduction to this chapter – the technology also faces several challenges. It should be noted that the more frequently an LED flickers, the brighter it becomes. This presents two issues: first, it leads to increased power consumption; second, if the same LED is being used for illumination, the emitted light may become too intense for the space in question [1, 2].

In such cases, various LED dimming techniques must be employed. Another challenge involves interference from other light sources – whether artificial (such as incandescent lamps) or natural (such as sunlight).

The presence of other light sources is perceived by the system as noise, which leads to a reduction in data transmission speed and an increase in the bit error rate (BER). Fortunately, it has been demonstrated that blue bandpass filters can limit the degradation

caused by solar radiation. Finally, light intensity drops sharply with distance, which may constrain the potential deployment scenarios.

VLC structural system

The basic structural diagram of a VLC system includes a transmitter and a receiver. A diagram illustrating this process is presented below.

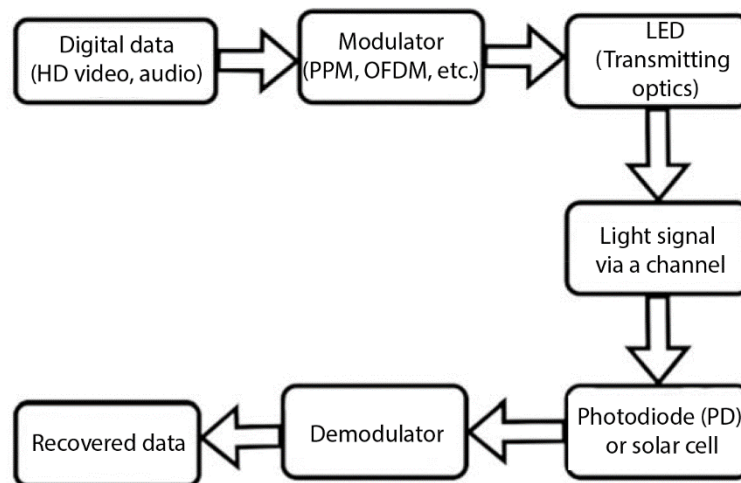


Fig. 1. Block diagram of a VLC system

Transmitter

A transmitter is designed to convert input electrical data into an optical signal, which is emitted by an LED (or an LED array) or a laser diode. Modulation, in essence, involves converting a data signal, $m(t)$, into a drive current for the LED (or laser diode), thereby creating a light signal, $x(t)$, whose intensity varies over time. This process is also known as optical intensity modulation. The resulting signal is transmitted over an optical channel to be received by a photodetector. The drive current must remain within the LED's dynamic range to avoid distorting the optical signal [1, 2].

Furthermore, the control signal must be real-valued and non-negative. Figure 2 also illustrates a dimming control unit, which is used to precisely adjust the LED's brightness to a desired level.

Dimming is employed for at least two reasons. First, it can be used to reduce the LED's brightness – for instance, when high data rates are required – while ensuring the resulting illumination meets the lighting requirements for a given environment. Second, it can help improve the LED's response time [4-6].

In indoor settings, LEDs are often preferred over laser diodes, partly due to their lower cost and wider field of view, and partly because they can also serve the purpose of general illumination. LEDs can be monochromatic (emitting a single color, typically blue, green, or red) or white (theoretically containing all colors simultaneously).

VLC systems are typically implemented using white light, which can be generated in several ways:

1) In the first method, red, green, and blue (RGB) light sources are emitted at specific intensities.

2) The second method is slightly more complex and involves using a blue LED coated with a phosphor material that emits yellow light. Thus, short wavelengths are absorbed, and yellow light is emitted. In the subsequent stage of light processing, the wavelength shifts toward the red end of the spectrum, where it combines with a portion of the blue light that was not absorbed. Ultimately, this results in white light with a specific spectrum. This method is more popular than the RGB approach, though it produces light with a limited bandwidth due to the relatively slow absorption and emission processes within the phosphor layer.

3) A third method generates broadband radiation that closely resembles the solar spectrum.

The optical configuration of an LED is also significant. Several implementation options are typically considered [2]:

- Direct approach, where light from the LED is emitted without passing through any optical device;
- Diffusive approach, where light is scattered to reduce surface brightness and expand the illumination range;
- Reflective approach, where light from the LED is directed via external reflectors;
- Transmissive approach, where a lens is placed in front of the LED to modify the light distribution pattern; and
- Combination of reflective and transmissive approaches.

It should be noted that there are several challenges associated with LED-based transmitters [2]. These include compensating for LED non-linearity, the need for precise control over LED chromaticity, and the aforementioned requirements for brightness control and flicker-free data transmission. Consequently, the power electronics used to drive LEDs play a critical role in the controlled transmission of VLC signals.

Receiver

The optical receiver is based on a photodetector. The photodetector receives the transmitted signal $x(t)$ – which has passed through a channel with an impulse response $h(t)$ – and generates a photocurrent $y(t)$.

Other key components of the receiver include an optical concentrator, which reflects and focuses the incoming light onto the photodetector, and an optical filter, which removes unwanted wavelengths. The optical filter can also be integrated into the optical

concentrator. An electronic amplifier is typically required within the receiver to process the detected current for subsequent stages of the receiver system.

There are at least three types of photodetectors: photodiodes, image sensors (including cameras), and solar panels. Among these, photodiodes are the most common. Commercial VLC systems typically employ two types of photodiodes: PIN photodiodes and avalanche photodiodes (APDs). While APDs offer higher gain than PIN photodiodes, they also suffer from higher shot noise. PIN photodiodes, by contrast, are inexpensive and exhibit greater temperature stability. Other types of photodetectors also offer distinct advantages; for instance, solar panels can simultaneously be used for energy harvesting, while camera sensors—already present in many devices, such as mobile phones—can be utilized for VLC with minimal additional cost [1, 2].

VLC channel and signal propagation model

Optical propagation links can be divided into two categories: line-of-sight (LOS) links and non-line-of-sight (nLOS) links. Due to the low reflection coefficient of light, LOS links are significantly more energy-efficient, and the amount of power reflected more than once is negligible. However, in indoor environments, there is typically at least one reflected path, which means that signals can still be detected even when obstacles are present. Propagation links can also be classified based on the directivity of the transmitter and the receiver. Both the transmitter and the receiver can be either directional or omnidirectional. Scenarios where one is directional and the other is not are referred to as "hybrid" links. When the presence of a LOS path is also taken into account, eight types of links can be identified:

- LOS / directional link
- LOS / omnidirectional link;
- LOS / hybrid link (directional transmitter, omnidirectional receiver);
- LOS / hybrid link (omnidirectional transmitter, directional receiver);
- nLOS / directional link
- nLOS / omnidirectional link
- nLOS / hybrid link (directional transmitter, omnidirectional receiver);
- nLOS / hybrid link (omnidirectional transmitter, directional receiver).

One of the fundamental differences between RF systems and optical systems is that RF systems are susceptible to multipath fading, whereas optical systems are not. This is because the physical detection area of a photodiode is significantly larger than the square of the wavelength of the incident light. Optical systems – especially outdoor, directional systems – are, by contrast, far more susceptible to pointing errors and pointing losses.

The attenuation in a VLC system can be modeled based on the signal loss that occurs as light propagates from the transmitter to the receiver. As previously mentioned, only two

paths are possible: the direct channel and the single-reflection channel. VLC channel attenuation can be characterized using the following model. A generalized Lambertian law can be applied to the transmitter side, indicating that the intensity of the emitted light depends on the cosine of the angle ϕ between the emitted light and the normal to the LED surface. Therefore, to calculate the path loss, one must first determine the Lambertian order as follows:

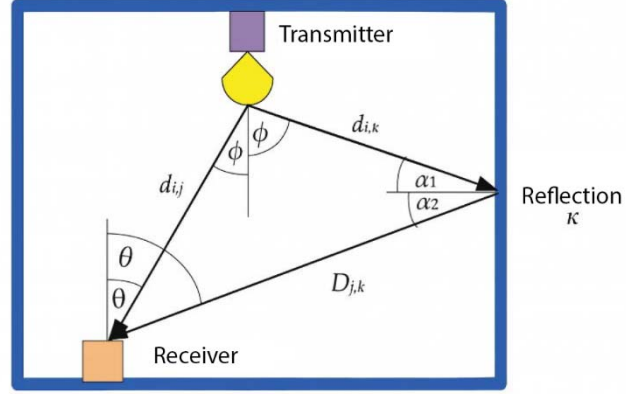


Fig. 2. Principle of optical wave propagation, accounting for both the direct ray and the reflected ray [1]

$$m = \frac{-1}{\log_2(\cos \theta_{1/2})} \quad (1)$$

where $\theta_{1/2}$ is the LED's emission angle at half-intensity. On the receiver side, the gain of the optical concentrator is equal to

$$f(\theta) = \begin{cases} \theta \frac{n^2}{\sin^2 \Theta}, & 0 \leq \theta \leq \Theta, \\ 0, & \theta > \Theta \end{cases} \quad (2)$$

where n is the refractive index and Θ is the field-of-view angle of the receiver photodiode. In this case, for a direct link, the DC gain (which is less than 1 – essentially an attenuation) can be expressed as

$$h_{i,j} = \frac{A_p(m+1)}{2\pi d_{i,j}^2} \cos^m \phi g_{of}(\theta) f(\theta), \quad (3)$$

where: A_p – the physical area of the photodiode, $d_{i,j}$ – the distance between the transmitter and the receiver, and g_{of} – the gain of the optical filter. In the case of $\theta > \Theta$ a direct line of sight, there is no [reflected component], and the DC gain is equal to zero.

For a reflected link, the DC gain can be determined using the formula

$$dh_i = \frac{A_p(m+1)}{2\pi d_{i,k}^2 d_{j,k}^2} \rho dA_s \cos^m \phi_r \cos \alpha_1 \cos \alpha_2 g_{of}(\theta_r) f(\theta_r) \cos \theta_r, \quad (4)$$

where $d_{i,k}$ is the distance from the transmitter to the reflecting surface, d_{jk} is the distance from the reflecting surface to the receiver, ϕ_r and θ_r are the angles associated with the reflection path, α_1 and α_2 are the angles of incidence and reflection at the point of reflection, and, finally, ρ is the reflection coefficient and dA_s is the effective reflecting area.

VLC channel capacity and throughput

The fundamental differences between RF and VLC systems mean that the capacity of a VLC channel does not correspond to the standard Shannon channel capacity. There are, in fact, two primary constraints on channel capacity: the requirement for non-negative real-valued signals and the limitation on average light intensity for the sake of eye safety. Furthermore, one must account for the illumination requirements of the environment in which the VLC system is deployed, as well as the dynamic range of the LEDs. Unfortunately, there is no analytical expression for channel capacity that incorporates both average and peak power constraints; one can only determine bounds (lower and upper) for the capacity.

These bounds vary depending on the specific constraints applied, and various alternative capacity limits have been proposed [1, 2].

An alternative metric to consider in the context of VLC is the achievable data rate (throughput). It has been established that the OFDM principle, which is widely used in RF systems, is also applicable to VLC. For a single user employing OFDM, the achievable data rate can be calculated using the following formula:

$$X_j = \frac{W}{\beta L} \sum_{i=1}^{\beta L-1} \eta_i \quad (4)$$

where W is the signal bandwidth, L is the number of subcarriers, β is a constant depending on the type of OFDM signal used (typically $\beta = 0.5$), and η is a subcarrier efficiency constant that accounts for the influence of the modulation scheme, the coding scheme, and the signal-to-noise ratio.

Modulation methods for VLC

Like RF transmitters, VLC transmitters require signal modulation for transmission over a wireless channel [13, 15]. However, there is a fundamental difference between modulation in the optical domain and in the RF domain. While RF modulation involves varying the frequency, phase, or amplitude of a signal, in the optical domain, one can only vary the intensity of the light emitted by an LED. Several categories of modulation schemes are considered for VLC, some of which bear similarities to those used in RF communications.

The modulation scheme for a specific VLC system is typically selected based on several criteria:

- Energy efficiency;
- Spectral efficiency (bandwidth utilization);
- Transmission reliability;
- Complexity;
- Robustness against external light sources.

Furthermore, all modulation schemes must eliminate long sequences of consecutive 0s or 1s, which could otherwise cause flickering, regardless of the data transmission rate. Additionally, it is necessary to ensure data recovery and clock synchronization.

Modulation schemes for VLC include:

- On-Off Keying (OOK);
- Pulse Amplitude Modulation (PAM);
- Pulse Position Modulation (PPM);
- Pulse-Interval Modulation (PIM);
- Pulse-Width Modulation (PWM).

Modulation OOK (On-Off Keying)

OOK is the simplest (and slowest) modulation scheme. In OOK, the LED is on if the transmitted signal is a binary 1, and off if the transmitted signal is a binary 0. Sometimes, instead of the complete absence of a signal in the 0 state, the LED simply emits light at a different intensity. If data is encoded using multiple levels of light intensity or amplitude, PAM modulation is achieved. The concept of PAM in the context of VLC is very similar to PAM in the RF domain.

Mathematically, a VLC signal can be expressed as:

$$s(t) = \begin{cases} A_c \cos(2\pi f_c t), & \text{if } b(t) = 1 \\ 0, & \text{if } b(t) = 0 \end{cases} \quad (5)$$

where: A_c – carrier amplitude, f_c – carrier frequency, $b(t) \in \{0,1\}$ – binary information signal.

Modeling and analysis of VLC system characteristics

As a result of the simulation, graphs showing the dependence of the Bit Error Rate (BER) on the Signal-to-Noise Ratio (SNR) were obtained. The simulation was performed using OOK modulation.

A total of 3,000 experiments were conducted, covering an SNR range from 1 to 15 dB with a step of 1 dB. The program utilized a LOS communication channel, with the OOK modulation corresponding to a VLC scenario under LOS conditions. Figure 3 presents the simulation results alongside the theoretical BER curves.

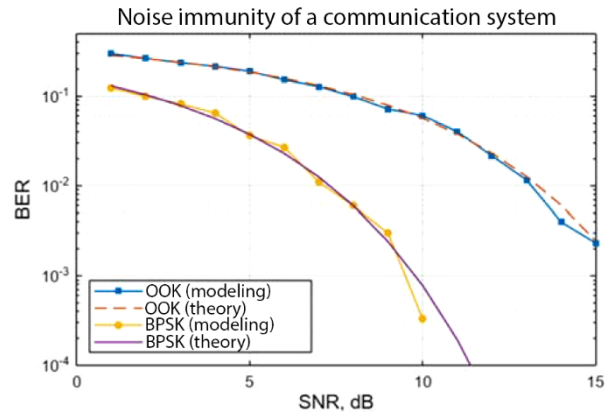


Fig. 3. Noise immunity of a communication system

The noise immunity of a VLC system improves more slowly as the SNR increases. At a BER 10^{-1} , BPSK modulation offers a 6 dB advantage over OOK; in other words, a VLC system requires a higher energy budget compared to a traditional radio communication system, and its communication range is limited – typically to just a few meters.

Analysis of simulation results for the VLC scenario.

First, there is a significant gap in noise immunity, with OOK underperforming relative to BPSK. This is expected and theoretically sound, as BPSK – a form of phase modulation—offers greater energy efficiency and better noise resilience than OOK, which is an amplitude-based modulation scheme. For instance, to achieve a bit error rate (BER) of approximately 10^{-3} , an OOK-based system requires an SNR that is about 5–6 dB higher than that of a BPSK-based system. This energy penalty is the trade-off for the simplicity of implementing OOK – a factor of particular relevance to VLC systems, which often utilize low-cost LEDs and photodetectors.

Second, it is worth noting the close alignment between the theoretical curves and the experimental (simulated) results for both modulation schemes. This indicates that the simulation was conducted with high precision and that the mathematical models used for the communication channel are accurate. The slight discrepancy between the "OOK (simulation)" and "OOK (theory)" curves in the moderate SNR range can be attributed to the fact that the simulation model accounts for real-world destabilizing factors inherent to optical channels – such as multipath propagation, photodetector noise, and transmitter nonlinearity – which are not considered in the basic theoretical model.

Thus, it can be concluded that, although OOK modulation is less energy-efficient than BPSK, its use in VLC systems is justified in terms of implementation simplicity and cost. The obtained results robustly validate the theoretical premises and support the use of this model for the further design and optimization of specific optical wireless communication systems [12].

Advantages of VLC

- Significant spectral resource: the visible spectrum is essentially unlicensed and has high potential for data transmission, theoretically enabling gigabit speeds with good equipment.
- Security and privacy: light does not penetrate opaque barriers, limiting coverage and reducing the risk of signal interception.
- No radio interference: VLC operation is possible in environments where RF radiation is undesirable or prohibited (medical facilities, aviation, industrial facilities).
- Dual-use: LED luminaires simultaneously provide illumination and data transmission, improving energy efficiency and cost-effectiveness.
- High positioning accuracy: localization using light beacons provides centimeter-level accuracy, useful for indoor navigation and contextual services.

Limitations and ways to overcome them

Key limitations of VLC and potential solutions:

Line-of-Sight (LoS) requirement: Data rates decrease when a direct path is obstructed. Solutions: use of multi-path receivers, distributed access points, and optical MIMO technologies.

Impact of ambient light: Introduces noise at the receiver. Solutions: use of optical filters, narrow-band receivers, and adaptive digital signal processing algorithms.

Uplink challenge: Difficulty in transmitting data from mobile devices. Solutions: hybrid architectures (VLC for downlink, RF or IR for uplink) and optical backscatter technologies.

Ensuring mobility: The need for seamless switching between light sources. Solutions: intelligent control systems with handover mechanisms.

Compatibility with lighting: Modulation must not cause perceptible flickering. Solutions: specialized modulation schemes and dimming algorithms that comply with lighting quality standards.

Areas of application, limitations, practical use

VLC systems are used in many areas of human activity, for example [1-4]:

– Li-Fi in offices and educational institutions: high-speed local network access, where each light fixture serves as an access point; useful for secure corporate networks and educational laboratories.

– Medicine: data transmission in intensive care units with minimal RF interference affecting medical equipment; secure data exchange between monitoring devices and a central system.

– Automotive (V2V and V2I): the use of headlights and brake lights to exchange short messages between vehicles – such as braking warnings or information for autonomous control systems.

Conclusion

VLC is a promising technology that complements traditional wireless systems in environments where the radio-frequency spectrum is congested. Its key advantages – high data security, the absence of electromagnetic interference, the capability for precise positioning, and its dual-purpose nature (providing both illumination and data transmission) – make VLC particularly valuable in sectors such as healthcare, industry, logistics, and secure corporate networks.

The future of VLC lies in its integration into next-generation (6G) hybrid networks, the miniaturization of components, and the advancement of standardization. In the coming years, the technology will be deployed in niche areas, while in the long term, it is set to become an integral part of smart city infrastructure, expanding connectivity options and laying the foundation for new services.

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