Research and Application of Visible Light Communication Technology

Chentao Xu *

Department of Communication Engineering, University of Shanghai for Science and Technology, Shanghai, China

* Corresponding Author Email: 2135062025@st.usst.edu.cn

Abstract. In recent years, the rapid growth of mobile devices and wireless services has created a significant demand for RF-based technologies. Among the various emerging wireless communication forms, Visible Light Communications (VLC) stands out as a potentially transformative technology that not only complements RF communications but also introduces innovative possibilities for mobile wireless device applications. VLC utilizes visible light for communication, offering high-speed data transmission, improved energy efficiency, and enhanced communication security and privacy. This article thoroughly explores VLC, discussing its core concepts, fundamental principles, and essential technologies that define this rapidly developing field. By providing insights into the intricacies of VLC, readers can gain a better understanding of its mechanisms and capabilities. The exploration also extends to elucidating the diverse application scenarios where VLC can be effectively applied, showcasing its versatility and potential impact on various sectors. This comprehensive survey not only presents the current state of VLC but also predicts future development trends, providing a forward-looking perspective on the evolution of this technology. As the demand for efficient and secure wireless communications continues to rise, VLC emerges as a promising frontier, poised to play a pivotal role in shaping the landscape of communication technologies in the years to come.

Keywords: Visible Light Communications; LEDs; mobile communication; wireless communication.

1. Introduction

Visible Light Communication (VLC) has emerged as a revolutionary technology in response to the changing societal and technological environment. In a world that heavily relies on wireless communication, VLC utilizes the visible spectrum to transmit data, providing distinctive benefits and a wide range of applications.

In the contemporary era, wireless communication has become an integral part of our daily lives. As the demand for faster, more secure, and energy-efficient data transmission continues to rise, conventional radio frequency (RF) systems are facing challenges related to spectrum congestion, interference, and security concerns. In response to these limitations, alternative technologies have been explored, leading to the emergence of VLC. Unlike traditional wireless communication systems, VLC utilizes the visible spectrum, which was previously untapped for communication purposes. This innovative solution offers a promising approach to overcome the limitations of RF systems.

VLC is a communication technology that utilizes LED luminaires to modulate light waves within the visible spectrum (380 nm to 750 nm). Advancements in LED technology, particularly in Gallium nitride (GaN) micro-LEDs, have greatly improved VLC capabilities. These micro-LEDs have impressive modulation bandwidths of over 800 MHz, allowing for data transmission rates of up to 5 Gbps. Ongoing research on materials like phosphors and innovative LED designs further contribute to the development of VLC as a reliable and efficient communication technology.

The significance of VLC research extends to various domains. In indoor positioning systems, VLC offers unparalleled precision, overcoming limitations associated with traditional radio frequency-based methods. In vehicular systems, Vehicle Visible Light Communication (V2LC) provides cost-effective and adaptable solutions for intelligent transport systems, demonstrating VLC's potential in enhancing vehicular communication efficiency and safety. The exploration of UAV-aided VLC introduces flexible and dynamic wireless communication in scenarios with limited terrestrial infrastructure, representing a crucial advancement for diverse applications.

VLC has a wide range of applications in various fields. For example, it can be used in indoor positioning systems that utilize techniques such as Received Signal Strength (RSS), Time of Arrival (TOA), and Angle of Arrival (AOA) to accurately calculate locations. In vehicular systems, V2LC enables communication between vehicles (V2V) and infrastructure, improving efficiency and safety. Additionally, UAV-aided VLC offers flexible wireless connectivity in situations where traditional infrastructure is insufficient or compromised.

The future of VLC appears promising, as ongoing research is expected to unlock new levels of efficiency and capability. Advancements in LED technology, materials research, and optimization techniques are anticipated to enhance data rates and broaden the range of VLC applications. Furthermore, the potential integration of VLC with emerging technologies, such as 6G scenarios and adaptive pre-equalization schemes, suggests that VLC could become a fundamental component of wireless communication technologies. As VLC continues to evolve, its role in shaping the next generation of wireless communication is poised to be pivotal.

VLC is a technology that combines technological innovation and societal needs. It possesses unique attributes, ongoing research endeavors, and diverse applications, making it a transformative technology with the potential to redefine the landscape of wireless communication in the foreseeable future.

2. Overview of Visible Light Communications

2.1. VLC concepts

2.1.1 What is VLC

The term "visible light communication" describes a method of data transmission that uses light waves in the visible spectrum, which has wavelengths ranging from 380 nm to 750 nm [1]. Visible light communication basically refers to any system that uses visible light for information transmission. But the primary goal of this communication is to transfer information in a fashion that is invisible to the human eye, such that the only illumination that is seen is normal ambient lighting with no discernible alterations. Similar technologies have given rise to other names, such as optical fidelity (Li-Fi) and optical wireless communication (OWC). The electromagnetic spectrum is shown in Figure 1, spanning from high-frequency gamma radiation to low-frequency radio waves. As discussed before, the visible light spectrum lies within the range of 380 nm to 750 nm. Visible light communication can be defined as any information conveyed within this range by altering light waves. It is significant to remember that the frequency range of wireless waves, which includes Wi-Fi technology, is 3 kHz to 300 GHz. On the other hand, the visible light spectrum spans frequencies from 430 THz to 770 THz, which is around 10,000 times more than the total radiofrequency spectrum.

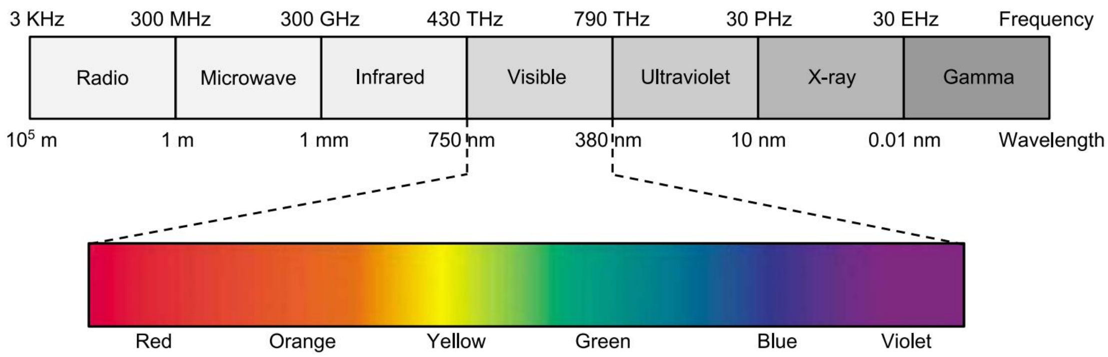

Fig 1. Electromagnetic Spectrum

2.1.2 History of VLC

Research on light-based communication systems has just recently been apparent, despite the increasing interest in VLC [1]. Light has always been one of the essential components that people have utilized to connect with one another throughout history. In the 1970s, interest in the study of communication using optical media increased. Studies conducted during this time period showed the possibility of wireless optical communication in interior settings, where THz-scale electromagnetic spectrum bands may be explored [2]. Up to one megabit per second of data might be sent using these systems. Infrared systems were able to reach data rates of up to 50 Mbps more recently, in the late 1990s. LED lights were first taken into consideration for VLC trials in the early 2000s. Tanaka et al. achieved a communication transmission rate of up to 400 Mbps by using a white LED bulb for both lighting and communication in an indoor environment. This signaled the start of a broad field of VLC study in the twenty-first century. Other researchers have since produced important discoveries, such as improved LED bulb technologies and novel modulation strategies. A key milestone in the history of Visible Light Communication was attained in 2011, when Harald Haas showed Li-Fi (Light Fidelity) for the first time during a TED Talk. In just a few months, this presentation received millions of views, demonstrating its enormous popularity. This innovation was warmly received by the academic community, which led to a significant rise in the amount of research being done in the area. At the moment, a lot of research is being done on VLC, and important people from the academic and business worlds are helping with research and product development [3].

2.2. VLC System

2.2.1 VLC transmitter

LED luminaires are the emitters used in visible light communication systems [1]. A full lighting device made up of an LED, a ballast, a housing, and additional parts is called an LED luminaire. One or more LEDs can be found in LED lights, commonly referred to as LED light bulbs. In order to alter the LED's brightness, the luminaire additionally has a driver circuit that modifies the current passing through it. The driver circuit is altered to allow data modulation utilizing the emitted light when LED illuminators are used for communications. For example, by choosing two different light intensity levels, the data bits '0' and '1' can be conveyed using basic on-off keyed modulation [4].

Lighting must be prioritized in VLC systems' design, and it must not be jeopardized by communication utilization [5]. Thus, the VLC system's performance is also impacted by the design of LED luminaires. Because white light renders colors similarly to natural light, it is frequently utilized for both indoor and outdoor lighting. There are two methods for producing white light in solid state lighting:1) Phosphorescent blue LED: This technique creates white light by covering a blue LED with yellow phosphor. White light is produced when blue light penetrates the yellow covering. You can achieve different color temperatures (or white light variations) by varying the phosphor layer's thickness.2) RGB combination: Red, green, and blue light can also be appropriately combined to create white light. When compared to employing blue LEDs with phosphors, this method requires three different LEDs, increasing the cost of the LED fixture [6].

The first method, which is less expensive and easier to apply, uses blue LEDs and phosphors in the design of white LEDs. However, in the context of communications, the phosphor coating imposes a limitation on the switching speed of the LED, reducing it to a few MHz. In contrast, the RGB combination is favored for communications because it permits the use of color shift keying, which makes it possible to use LEDs with three distinct color wavelengths for data modulation.

2.2.2 VLC receiver

There are two primary types of VLC receivers designed to capture signals emitted by LED luminaires: 1) the photo detector, also known as a photodiode or non-imaging receiver, and 2) the imaging sensor, commonly referred to as a camera sensor [1]. The photo detector, a semiconductor device, plays a crucial role in converting received light into electrical current. Currently, commercially available photo detectors can efficiently sample visible light signals at rates reaching tens of megahertz. In addition to the photo detector, an alternative option is the imaging sensor, which is essentially a camera sensor. Given that camera sensors are ubiquitous in modern mobile devices, such as smartphones used for capturing images and videos, they hold the potential to transform these devices into accessible VLC receivers. An integrated circuit containing a matrix of photodetectors makes up the structure of an imaging sensor. One significant disadvantage of imaging sensors is that they are not suitable for high-resolution photography, since this type of photography necessitates a large number of photodetectors [7]. Unfortunately, the number of frames per second (fps) that may be recorded is greatly reduced by the additional photodetectors. For example, most widely used smartphone camera sensors have a maximum frame rate of no more than 40 [8]. As such, a relatively low data rate is obtained when using a camera sensor directly for visible light communication. It is important to note that any mobile device with a camera can serve as a visible light communication receiver thanks to the presence of an imaging sensor. However, at present, its usefulness is limited to providing a modest throughput, usually a few kilobits per second (kbps), mainly because of its very low sampling rate. Conversely, independent photodetectors have proven to be able to attain far higher throughputs, frequently hitting hundreds of megabits per second (mbps) [6].

3. Researches on VLC

3.1. Research on materials

Visible Light Communication is a rapidly advancing wireless communication technology that utilizes the visible spectrum within the electromagnetic spectrum. It offers an alternative to traditional radio frequency (RF) systems. Gallium nitride (GaN) light-emitting diodes (LEDs), particularly micro-LEDs, play a crucial role in propelling VLC forward [9]. These micro-LEDs are smaller than $100\times100\mu m^2$ and have achieved impressive modulation bandwidths exceeding 800 MHz, enabling data transmission rates of up to 5 Gbps. This achievement opens up possibilities for high-speed data transmission in both free-space environments and along polymer optical fibers (POF), representing a significant advancement in VLC capabilities. The innovative designs of these LEDs not only demonstrate exceptional modulation capabilities but also highlight the adaptability of VLC within existing lighting infrastructure. By leveraging off-the-shelf LEDs and advancements in LED epitaxial structures specifically optimized for VLC, it solidifies its position as a versatile and efficient wireless communication technology. Ongoing research, particularly in LED design factors like deep etching of the mesa, improved metallization, and shaping of the active area, holds the promise of further enhancing VLC performance. In addition to advancements in LED technology, the study of phosphors in VLC applications is also of great importance. Different types of phosphors, such as those doped with erbium and nitride phosphors like Sr2Si5N8, have significant roles in various applications, including improving solar cell efficiency and producing white LEDs. These phosphors not only contribute to illumination but also enhance the overall efficiency and functionality of VLC systems. Continuously exploring and integrating state-of-the-art technologies in LED design and phosphor utilization have the potential to further enhance the efficiency and capabilities of VLC.

An intriguing proposal that has garnered attention involves the utilization of CaAlSiN3:Eu2+ phosphor for visible light communication [10]. This phosphor is specifically designed to tackle long-distance communication challenges. It offers a compelling solution by transforming high-energy photons into low-energy photons within the H-α band, effectively compressing the spectrum. This transformation results in a shift from wide-spectrum VLC to a more targeted, narrow-spectrum approach. Experimental findings showcase remarkable outcomes, including an impressive 50% light energy conversion efficiency, a minimal code delay of 0.25μs, and an outstanding optical efficiency of 95%. This innovative solution markedly enhances received light intensity, positioning it as a promising avenue for both indoor and outdoor long-distance VLC applications. In summary, the synthesis of advanced GaN LED technologies and the inventive application of phosphors present a comprehensive snapshot of the current state and future prospects of VLC research. The synergistic combination of LED advancements and phosphor innovations not only enhances data transmission rates and modulation capabilities but also broadens the applications of VLC in diverse fields, such as high-speed data transmission, agriculture, and renewable energy. As researchers delve deeper into understanding LED structures, refining phosphor properties, and optimizing communication protocols, VLC continues to maintain its position at the forefront of the next generation of wireless communication technologies. The ongoing exploration and integration of cutting-edge technologies in VLC promise to unlock new realms of efficiency and capability in the realm of visible light communication.

3.2. Research on Channels, Adaptation, and Optimizations

Due to its potential to offer high-speed access in upcoming 6G scenarios, LED Visible Light Communication has drawn attention. A deep learning model-based adaptive digital pre-equalization method is provided in Yang et al.'s study [11] for visible light communication channels in order to boost data rate. This makes the scheme a universal digital solution for high-speed access in 6G scenarios when combined with the VLC spectrum. With an emphasis on the useful uses of VLC networks, Schmid et al. verified the potential of LED-to-LED VLC adhoc networks as a helpful technology for sensor networks, smart and connected consumer gadgets, and the Internet-of-things. Additionally, Zhu et al. highlighted the need for sophisticated channel models in future communication systems and provided a novel 3D non-stationary channel model for 6G indoor VLC systems, reflecting distinctive indoor VLC channel features. Additionally, Jung et al.'s study examined how the wavelengths of the LED transmitter and receiver in a full-duplex LED-to-LED VLC system affected performance, highlighting the significance of taking hardware-related parameters into account when improving VLC system design. Zhou et al. demonstrated the potential of improved equalization approaches for increasing VLC transmission speed in a different work where they suggested a two-staged linear software equalizer for high-speed VLC transmission, attaining a data rate of 2.32 Gbit/s based on a phosphorescent white LED. Furthermore, Wu and Fan's study, LED Visible Light Communication Channel Model Based on Poisson Stochastic Network Theory, highlighted the relevance of stochastic network theories in channel modeling by producing simulation results that highlighted the suitability of the suggested scheme for determining the ideal arrangement of LED lamps in visible light communication systems. To sum up, the literature that has already been written about LED visible light communication systems demonstrates the increasing interest in these systems as well as the need for sophisticated channel models, flexible pre-equalization schemes, and hardware-dependent optimizations to improve data rates and make practical applications possible in a variety of settings.

4. Application of VLC

4.1. VLC Indoor Positioning System

Visible Light Communication has emerged as a transformative technology for indoor positioning applications, offering unparalleled precision and accuracy. In this comprehensive overview, we explore various techniques, systems, and recent advancements in VLC-based indoor positioning. We highlight notable examples and address existing challenges [2]. Figure 2 roughly depicts this scene. Achieving precise positioning with VLC involves receivers capturing signals from room LEDs and using algorithms to calculate distances, thereby determining the exact position of the receiver. Common techniques include Received Signal Strength (RSS), Time of Arrival (TOA), and Angle of Arrival (AOA). RSS-based methods have limitations due to signal weakening over distance and potential interference from obstacles. TOA requires synchronized signals, which may increase system costs. AOA, typically impractical in radio frequency systems, finds viability in VLC systems due to the Line of Sight (LOS) communication requirement. The Epsilon system, introduced in 2014 by Liqun Li et al., pioneered practical indoor tracking. It employs trilateration based on RSS, achieving high precision with a minimal 0.4 m error at a low cost. Luxapose, also introduced in 2014, utilizes smartphone image sensors for localization and achieves an impressive 0.1 m error rate through triangulation based on AoA and smartphone orientation. These systems demonstrate VLC's potential for accurate indoor positioning, surpassing traditional radio frequency-based methods. Hybrid positioning systems, which integrate VLC with existing technologies like Bluetooth or RFID, offer a synergistic approach. Prince and Little proposed a hybrid VLC positioning algorithm that combines RSS and AoA for precise receiver location. In 2014, Yang et al. presented a model that incorporates multiple receivers and transmitters, utilizing RSS and AoA to achieve high-precision positioning. These hybrid approaches harness the strengths of VLC alongside established technologies, showcasing versatility and robustness. The industry's interest in VLC-based positioning is evident through commercial systems like ByteLight13, signaling active exploration and investment in VLC localization applications. Liu et al. emphasize performance metrics as crucial benchmarks, highlighting the advancements in precision and accuracy achievable through VLC-based systems. While VLC-based indoor positioning has showcased significant capabilities, addressing challenges related to robustness, scalability, and complexity remains an ongoing research focus. In conclusion, VLC-based indoor positioning stands as a pivotal application with substantial potential for the future. The technology's unmatched precision and accuracy have garnered attention from academia and industry alike. While notable systems showcase VLC's capabilities, ongoing research endeavors are crucial to address challenges and enhance the overall performance of VLC-based indoor positioning systems, ensuring their robustness, scalability, and continued success in diverse applications [12].

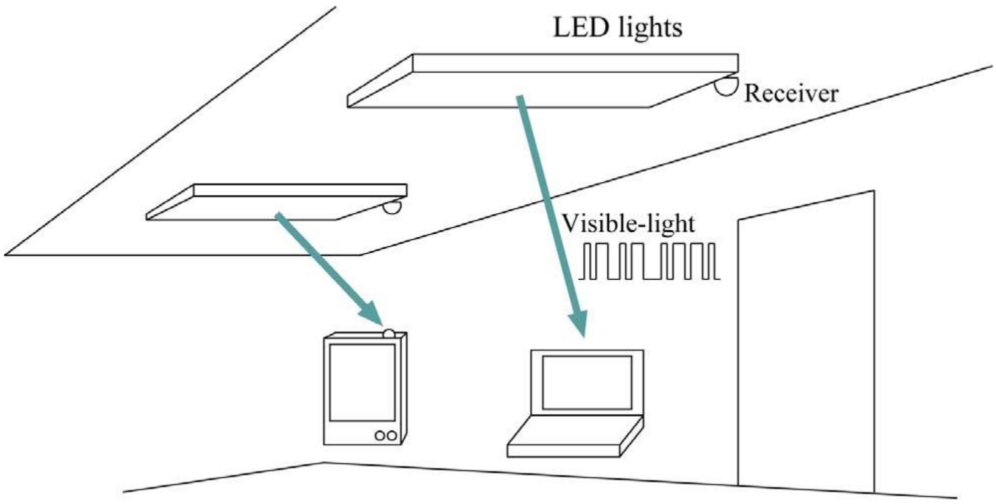

Fig 2. Indoor Positioning System

4.2. Transport and Vehicular Systems

Visible Light Communication has found a promising niche in the transportation and autonomous vehicle sector, leveraging the widespread adoption of LED bulbs in various industries. Specifically, Vehicle Visible Light Communication (V2LC) in vehicular systems offers several advantages in terms of cost, complexity, and adaptability to existing infrastructure [2]. V2LC involves dynamic communication networks consisting of mobile nodes (vehicles) and fixed structures like traffic lights and streetlights. Both types of nodes can be equipped with transmitters and receivers, creating a robust system capable of collecting and disseminating information from various sensors in vehicles and their surroundings. This integration makes V2LC an essential component of Intelligent Transport Systems (ITS). In 2001, a groundbreaking V2LC system was developed, utilizing LED bulbs for a traffic information system. This showcased the potential of visible light in transmitting data related to traffic control, location of traffic lights, and vehicle movements. This early application laid the foundation for further advancements in VLC for vehicular communication. The characteristics of the propagation channel play a crucial role in communication quality, particularly in dynamic environments like in-vehicle communications. Cheng et al. compared light and radio waves, emphasizing the advantages of the optical channel, such as high transfer rates, low cost, and spatial efficiency due to Line of Sight

(LOS) communication. The LOS requirement aligns well with the nature of vehicular systems, where visibility is often a key factor.

Vehicular networks in VLC extend to direct communication between cars, known as Car-to-Car (C2C) or Vehicle-to-Vehicle (V2V) communication. In this scenario, a car's headlamp can function as a transmitter, while photodiodes act as receivers for bidirectional communications. The feasibility of V2V VLC has been demonstrated in various studies, where experiments have achieved impressive speeds and shown resilience to noise and interference. Researchers have categorized V2LC services into different groups and developed prototypes based on accessible hardware devices, analog techniques for noise resistance, and flexible programming environments for algorithm implementation. Simulation results have indicated that V2LC meets the latency and distance requirements for high-density vehicle scenarios. Practical demonstrations of V2V VLC systems have been conducted using car headlights as communication devices. Yoo et al. utilized commercial LED headlamps and driver modules, ensuring compliance with regulations. They successfully addressed challenges such as interference from other light sources and achieved data transmission rates of up to 10 Kbps at distances exceeding 30 meters during daylight.

Despite the evident benefits of VLC in vehicular environments, challenges persist. The presence of outdoor environments and multiple light sources can cause interference, which necessitates the development of innovative solutions such as color filters to mitigate unwanted signals. However, the vehicular environment provides a fertile ground for exploring VLC, encompassing intra-vehicle communication as well as communication with external elements like traffic lights. In conclusion, Visible Light Communication has emerged as a transformative technology in the transportation and autonomous vehicle sector. V2LC, with its adaptability to existing infrastructure, cost-effectiveness, and potential for high-speed communication, demonstrates the diverse applications of VLC in improving the efficiency and safety of vehicular systems. Ongoing research and innovations are crucial to address challenges and further enhance the robustness of VLC in this dynamic and critical domain [13].

4.3. Unmanned Aerial Vehicle Systems

Due to their affordability and portability, unmanned aerial vehicles (UAVs), also referred to as drones, have found widespread use in both military and civilian applications [14]. Recent technological developments, such lower costs and smaller devices, have increased public accessibility to small UAVs. Because of their accessibility, UAVs are finding new uses in both the commercial and civilian sectors. Among these uses, unmanned aerial vehicle (UAV) assisted wireless communications have drawn a lot of interest as a potentially useful way to offer adaptable wireless access, particularly in situations when ground infrastructure is either damaged or insufficient. Three main uses for UAV-assisted wireless communications have been identified by the literature so far: UAV-assisted data gathering and distribution, UAV-assisted relaying, and UAV-assisted ubiquitous coverage. Moreover, cooperative endeavors incorporating several UAVs have been investigated to establish effective communication systems. Traditionally, radiofrequency bands have been used for UAV-assisted wireless communications, where users, base stations, and UAVs fight for scarce spectrum resources. A growing body of research has looked into the application of visible light communication technologies in UAV networks to address issues related to spectrum limits.

UAV-aided Visible Light Communication offers several advantages in terms of utilizing additional spectrum resources to achieve high data rates and confining light signals to specific areas, thus preventing data eavesdropping and unauthorized intrusion. Previous research has primarily focused on optimizing UAV deployments by considering various performance metrics. For instance, optimization problems have been formulated to minimize total power consumption through joint optimization of UAV deployment and cell association. To further enhance optimization solutions, deep learning methods have been employed. Moreover, sum rate optimization has been explored in UAV-VLC systems using nonorthogonal multiple-access techniques. Additionally, research efforts have also addressed UAV-aided VLC networks where UAVs act as relays, optimizing UAV position and block length allocation to reduce error probability.

Although a lot of study has been done on UAV-assisted visible light communication, prior studies have mostly concentrated on transmitters and receivers oriented vertically downward and upward, ignoring the jittering effect at the UAV's side. This jittering effect causes uncertainty in the orientation of the UAV and changes in the intensity of the light stream, setting UAV-aided VLC apart from traditional VLC. Our letter responds to this by presenting a stochastic model that includes UAV jitter for VLC channels assisted by UAVs. The following are our model's main contributions: a model that provides closed-form formulas for the tilt angle's cumulative distribution function (PDF) and probability density function (PDF) resulting from UAV jitter-induced orientation errors. The Lambertian model is used to derive the received power distribution, taking random UAV jitter into account. The fluctuation of received power is found to be dependent on the relative position of the UAV and the level of jitter. Validation of our analytical expressions through simulation and experimental results. In conclusion, UAV-aided VLC shows promise as a wireless communication solution in scenarios with limited terrestrial infrastructure. Our proposed stochastic model addresses the fundamental jittering effect in UAV-aided VLC channels, contributing to a more comprehensive understanding of the statistical properties of these communication links. Ongoing research in this field is crucial for further advancements in UAV-aided VLC technology.

5. Conclusion

This paper presents a comprehensive overview of Visible Light Communication, covering its concepts, historical evolution, system components, current research trends, and diverse applications. With the growing dependence on wireless communication in society, VLC emerges as a transformative technology that offers distinct advantages and addresses the limitations of traditional radio frequency systems.

The historical journey of VLC, from early experiments in the 1970s to the groundbreaking demonstration of Li-Fi by Harald Haas in 2011, showcases the continuous development and increasing fascination with light-based communication. The use of LED luminaires as transmitters, particularly with advancements in GaN micro-LEDs and phosphors, emphasizes the crucial contribution of materials research in improving VLC capabilities.

VLC's applications span across various domains, with notable emphasis on indoor positioning systems, vehicular communication (V2LC), and UAV-aided wireless communications. In the field of indoor positioning, VLC surpasses the precision of traditional radio frequency-based methods, thereby paving the way for enhanced location-based services. V2LC offers cost-effective and adaptable solutions for intelligent transport systems, highlighting the potential of VLC in improving vehicular communication efficiency and safety. Additionally, UAV-aided VLC enables flexible wireless connectivity in scenarios with limited terrestrial infrastructure, opening up new possibilities for applications such as disaster response and environmental monitoring.

The ongoing research on materials, advanced LED technologies, and optimization techniques indicates the continuous development of Visible Light Communication. Noteworthy advancements include the use of gallium nitride micro-LEDs, innovative LED designs, and the exploration of adaptive pre-equalization schemes for 6G scenarios. These efforts demonstrate a commitment to pushing the limits of VLC capabilities. Furthermore, the integration of VLC with emerging technologies holds promise for its future as a fundamental component in wireless communication.

As VLC continues to evolve, its impact on diverse applications and its potential to redefine wireless communication paradigms are becoming increasingly evident. The synergy between technological innovation and societal needs positions VLC as a transformative force with the potential to shape the future of wireless communication. This paper serves as a testament to the growing significance of VLC and the exciting prospects it holds for the next generation of communication technologies.

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