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Next-Generation Wireless Communications using Optical and Visible Light

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Abstract

Visible light communication (VLC), or LiFi, is a potential technique for next-generation wireless networks, particularly indoors. It uses light-emitting diodes (LEDs) for lighting and data transmission. LEDs have various advantages over traditional lighting sources, including longer lifespan, higher tolerance to humidity, faster switching speeds, lower cost, and lower power consumption. Recent advancements have made LEDs even more efficient, enabling them to handle not only lighting and data communication but also indoor positioning and sensing in various applications. Li-Fi, or Light Fidelity, refers to Visible Light Communication (VLC) systems that use light emitting diodes as a medium for high-speed communication. The LI-FI System comprises of headlights, such as LEDs, that operate as transmitters and photo sensors, which act as receivers. With the proliferation of electronics, their use and growth led to advancements in Wi-Fi, which now provides a technology known as Li-Fi. Li-Fi is a technology that uses LED light to carry data quicker and more versatile than Wi-Fi. Because light can go almost anywhere, communication may follow suit. Underwater communications and sensor networks are now the subject of substantial ongoing research in area of high speed communications. This paper delves into the latest research and advancements in VLC systems. It explores new techniques and modulations, VLC channel characteristics, communication using optical cameras, visible light position-ng, and even underwater and vehicular applications. The presented research aims to address the challenges faced by VLC and propose solutions to over-come them.

Keywords: Infrared, optical spectrum, ultraviolet, visible light, wireless communication

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1. Introduction

Instead of radio waves, optical wireless communication uses light waves to transmit information. It's a new technology that can be used alongside existing radio-frequency wireless systems. Visible light communication (VLC) is a type of optical wireless communication that uses visible light. VLC has become increasingly popular in recent years. Other forms of optical wireless communication use light that is invisible to the human eye, like infrared (IR) and ultraviolet (UV) light.

The optical spectrum encompasses all forms of light perceptible by the human eye (visible light) along with invisible light waves. These invisible waves include infrared with longer wavelengths and ultraviolet with shorter wavelengths.

Infrared (IR) radiation, is a kind of invisible energy wave, similar to light but felt as warmth. It's different from the colors we can see because its waves are longer. Anything warmer than about-450°F (-268°C) gives off IR waves. The sun releases a lot of its energy as IR, even though some of its light appears colored to us.

Visible Light, the world around us is filled with a dazzling display of colors, and how bright things appear is all thanks to a tiny slice of a vast energy wave called the electromagnetic spectrum. Our eyes can capture only a specific range of these waves, from the incredibly tiny ripples starting at violet around 400 nanometers, all the way to the fiery red at 700 nanometers (a nanometer is a billionth of a meter!). This range is called visible light. The ultimate light show in the sky, the Sun, is the main source of visible light. We also have man-made light sources, but visible light does more than just illuminate our surroundings.

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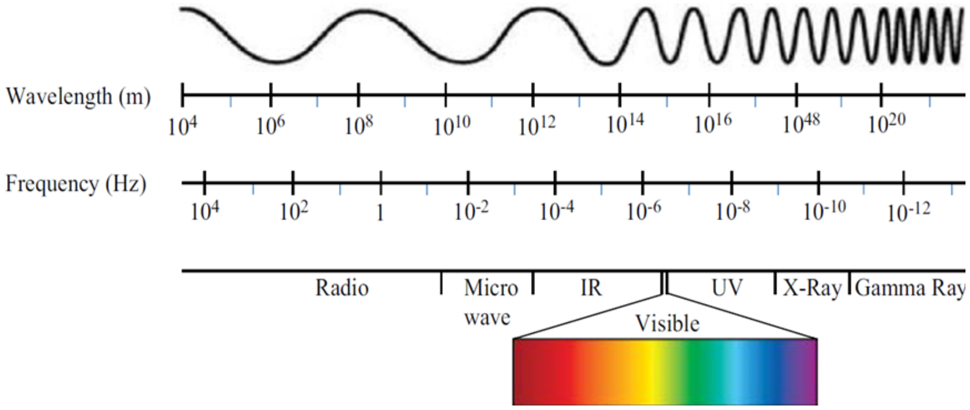

Fig 1: The Ultraviolet, visible, and IR portions of the electromagnetic spectrum: wavelength and energy.

Ultraviolet, Imagine a spectrum of light, like a rainbow, but much bigger. We can only see a tiny portion of this spectrum with our eyes, which is what we call visible light. Just beyond the violet end of visible light lies a type of radiation called ultraviolet (UV) light. Think of UV light as invisible rays with higher energy than visible light, but lower energy than X-rays. There are three main categories of UV light, each with slightly different properties: UV-A, UV-B, and UV-C.

2. Background

Since ancient times, there have been ingenious methods of conveying information using light. Early versions of optical wireless communication (OWC) included the use of smoke signals, blazing flames, torches, and even sunlight. One of the first reported examples is from circa 800 BC, when Greek and Roman warriors used polished shields to reflect sunlight and flash messages during battle. Similarly, in ancient time, troops stationed along the important places employed smoke signals emanating from beacon towers to warn of oncoming attackers. The careful installation of these towers at regular intervals enabled long-distance communication across thousands of kilometers. Heliographs, a military communication instrument that uses a pair of mirrors to broadcast controlled beams of sunlight during the day or other powerful light sources at night, first appeared in the nineteenth century. Alexander Graham Bell and his partner invented the photo-phone in 1880, which was an important milestone in OWC history. This technology employed light to convey speech signals, with the speaker's voice vibrating and being reflected by sunlight before being transformed back to sound at the receiving end.

Laser diodes (LDs) and light-emitting diodes (LEDs) are now the standard light sources in OWC systems constructed today. Wireless infrared communication, visible light communication (VLC), and wireless ultraviolet communication are the three primary categories into which these systems are divided according to the wavelengths at which they operate.

3. Research Elaborations

3.1. Wireless Infrared Communications

An ingenious concept came up decades ago: transmitting data wirelessly over short distances using infrared light beams, which are invisible light beams. These infrared (IR) gadgets became celebrities in the world of remote controls for TVs, air conditioners, DVD players, and even electronic toys because they are generally feather-light, affordable, power-thrifty, and easy to create. Engineers even tried an indoor wireless system that used 950 nanometer infrared light for broadcasting back in the 1970s. This system could connect a group of data terminals within a range of 50 meters, proving IR's potential for more than just remotes.

In the early days, different companies' devices that used infrared (IR) for communication couldn't talk to each other. This caused problems, so the tech industry decided to create a common language for IR. In 1993, a group funded by companies called the Infrared Data Association (IrDA) was formed. Their job was to define the exact way IR signals would be sent and received, like a universal translator for short-distance wireless communication between devices like laptops, phones, and printers.

Every component of the optical spectrum is described in depth in Table 1. Commercial IrDA devices provide data speeds between 9.6 kbps and 16 Mbps over short line-of-sight distances, from a few meters to under a meter. The MAC layer uses a number of protocols, including Object Exchange (OBEX), Infrared Communications (IrCOMM), and Infrared Mobile Communications (IrMC). 100 Mbps is also supported via the Ultra-Fast Infrared (UFIR) protocol. These devices run in half-duplex mode since there is a chance that transmitted light will interfere with the optical receiver.

In contrast to IrDA, IR WLAN systems do not require line-of-sight, utilizing reflections off walls and ceilings for signal propagation. They can operate independently in adjacent rooms, minimizing interference and reducing the risk of eavesdropping.

For long-distance transmissions, such as inter-building linkages in metropolitan or campus-area networks, infrared laser communication systems are employed. These systems are just point-to-point, and they can be affected by weather patterns like fog.

Table 1: Optical Spectrum detail.

Band		Wavelength	Frequency
Infrared	Far infrared (FIR)	15-1000 μm	300 GHz to 20 THz
	Long-wavelength infrared (LWIR)	8-12 μm	20-37 THz
	Mid-wavelength infrared (MWIR)	3-8 μm	37-100 THz
	Short-wavelength infrared (SWIR)	1.4-3 μm	100-214 THz
	Near infrared (NIR)	0.75-1.4 μm	214-400 THz
Visible	Red	625-750 nm	400-480 THz
	Orange	590-625 nm	480-510 THz
	Yellow	565-590 nm	510-530 THz
	Green	500-565 nm	530-600 THz
	Cyan	484-500 nm	600-620 THz
	Blue	450-485 nm	620-670 THz
	Violet	380-450 nm	670-790 THz
Ultraviolet	Near-UV (NUV)	300-400 nm	750 THz to 1 PHz
	Middle-UV (MUV)	200-300 nm	1-1.5 PHz
	Far-UV (FUV)	122-200 nm	1.5-2.46 PHz
	Hydrogen Lyman-α	121-122 nm	2.46-2.48 PHz
	Extreme-UV (EUV)	10-121 nm	2.48-30 PHz

3.2. Visible Light Communications

Ultraviolet C light (UV-C, between 100 and 290 nanometers) stands out within the whole ultraviolet range (10 to 400 nanometers) as a promising choice for wireless communication. This is for two key reasons.

Unseen Paths: Unlike traditional radio waves, UV-C light can bend around obstacles and bounce off particles in the air. This allows for communication even when the transmitter and receiver aren't in direct line of sight.

Quiet Channel: The Ozone layer filters out the majority of sunlight before it reaches the Earth's surface, particularly in the UV-C band. This creates an almost silent communication channel with very little background noise to disrupt the signal.

These two factors combined make UV-C ideal for setting up connections that don't re-quire a clear line of sight. The receivers used in these systems have wide fields of view to capture the scattered light signals, even when they bounce off particles in fog or haze.

Before World War II, at the US Naval Research Laboratory, the idea of employing ultraviolet (UV) light for wireless communication outside in naval applications was initially proposed. By 1968, MIT Lincoln Laboratory researchers had constructed an experimental device to test a 26-kilometer long long-distance link. The UV source in this early system was a potent xenon flash tube, which produced a continuous spectrum with wavelengths as low as 280 nanometers, and a photomultiplier tube for receiving the signal (as described in Xu and Sadler's 2008 work). How-ever, due to the bulky size, high energy consumption, and significant cost of these UV transceivers, research in this area stalled for several decades.

The development of commercially available semiconductor light sources in the 2020s brought new life to wireless UV communication. These new sources enabled the creation of transceivers that were smaller, cheaper, used less power, and offered much larger bandwidths. Using short-range UV-C linkages, researchers carried out a number of outdoor trials (up to 100 meters). Using photomultiplier tubes as detectors and either LED arrays or laser diodes as the light source, they constructed unique hardware platforms. These experiments allowed them to gather channel data and develop models to under-stand how the signal scatters in the environment.

3.3. Wireless Ultraviolet Communications

Communication systems that use light beams outside of buildings, also known as FSO communication, typically use wavelengths of light just beyond what we can see because this light weakens less as it travels compared to visible or ultraviolet light. FSO systems use devices that emit very concentrated beams of light, rather than simpler light emitters, to create strong light signals for data transmission. These beams are tightly focused to create a connection between the sender and receiver, but this also makes it challenging to keep the light beam precisely aimed. For this reason, FSO systems work best when transmitting large amounts of data rapidly across short distances (a few meters to several thousand kilometers) between two permanent points. FSO lines can carry a lot more data at once than radio frequency-based communication, which enables considerably quicker data transfer. Long-distance communication speeds of up to 10 Gbps have already been attained, and a 40 Gbps FSO connection has already been put into place.

4. Studies and Findings

4.1. Optical Transceiver

An OWC system works like a high-tech flashlight for data. Here's how:

Encoding the Message: At the sending station (transmitter), information is turned into pulses of light. Imagine flickering a light switch according to a secret code. Lightening the way: A special device called a light-emitting diode (LED) or a laser diode creates these light pulses, carrying the encoded message.

Sending the Signal: The light pulses travel through the air, similar to how a flashlight beam shines outwards.

Catching the Light: On the receiving end, a photodiode detects the incoming light pulses.

Decoding the Message: The receiver interprets the light pulses and translates them back into the original information, just like deciphering a secret code from flickering lights.

An optical transmitter acts like a translator, taking information and converting it into a light signal for travel. Here's a breakdown of its parts:

Light Source and Driver: This is the heart of the transmitter, where electricity is turned into light. LEDs with collimators are common for shorter distances, while powerful laser diodes are used for longer ranges in Free-Space Optical (FSO) systems. The driver circuit ensures the light source operates efficiently.

Encoder: Information, like a computer file, is first transformed into a format suitable for transmission. The encoder acts like a secret code maker, converting the data into a special pattern.

Modulator: This component takes the coded information and uses it to control the intensity of the light coming from the source. Imagine the modulator as a dimmer switch, adjusting the light's brightness based on the code.

Lens/Beam Shaper: Just like focusing a flashlight beam, a lens or beam shaper concentrates the light from the source into a tight beam for efficient transmission.

Here's a twist, depending on the distance, the light source changes. LEDs are like flashlights, good for shorter distances. For longer ranges, like FSO systems, laser diodes are like powerful searchlights, enabling light to travel much farther.

When choosing components for an optical transmitter, there's a balancing act:

Small Size and Low Power Consumption: Ideal for compact devices.

High Optical Power: Ensures the signal travels far enough.

Wide temperature ranges: The transmitter should work well in hot or cold environments.

Long Lifespan (MTBF): We want the transmitter to last a long time between failures.

The good information is that many pre-made components exist for these specific needs. Popular wavelengths for FSO systems are 850nm and 1550nm. These wavelengths experience less signal weakening over long distances and conveniently match the standard wavelengths used in fiber optic communication systems.

In optical wireless communication (OWC), information can be sent using pulses of light. We can control how bright (intense) these pulses are or when they happen to send the message. Basic methods like turning the light on and off (on-off keying) or shifting the timing of the pulses (pulse-position modulation) can be used. For even faster transmission, more advanced techniques can be employed, such as combining multiple colors of light (wavelength-division multiplexing) or sophisticated pulse control (Orthogonal Frequency-Division Multiplexing, OFDM).

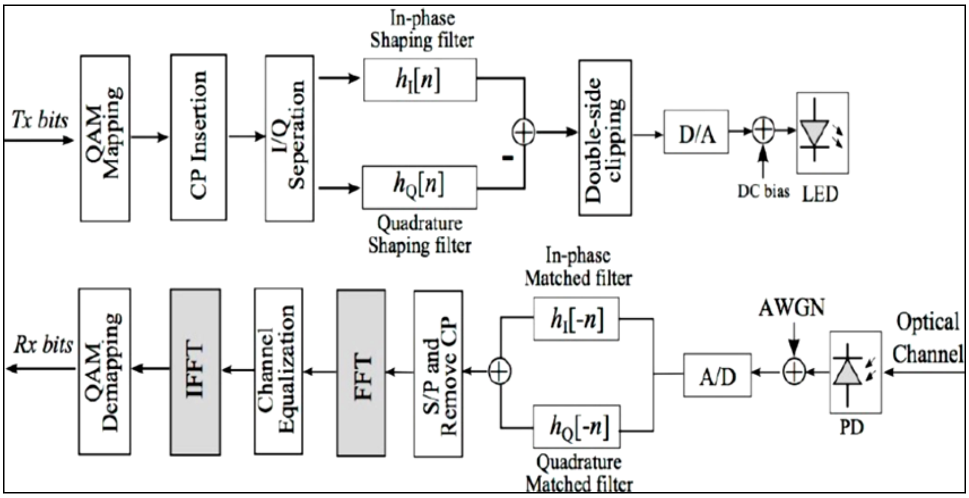

Fig 2: Optical Wireless Communications System.

OWC can handle multiple users by using various techniques. Similar to sharing a cable, it can take turns letting different users transmit (time-division), assign different colors of light to different users (wavelength-division), or use a special code for each user (code-division). Additionally, OWC can take advantage of having multiple light sources and detectors, similar to advanced radio systems (MIMO), to improve communication efficiency.

The frequency and the wavelength of the emitted or absorbed photon is related to the difference in the energy E as given by, i.e.

$$E = E_2 - E_1 = hf = \mathrm{hc}/\lambda \quad (1)$$

If the drive current of an LED is modulated at a frequency of ω then the relative optical power output at any given frequency is given as-

$$P(\omega)/Po = 1/\sqrt{1 + (\omega\Gamma ic)^2} \quad (2)$$

$$P_{\mathrm{max-in}} \geq x(t) \geq 0 \quad (3)$$

Where, $P_{\mathrm{max-in}}$ is the transmitter's maximum instantaneous optical power. Thus, only a small amount of route loss may be allowed in optical systems, and correspondingly large optical transmit powers are needed. Given that the average optical transmit power is constrained, it is most advantageous to employ modulation schemes with a high peak-to-mean power ratio. This is often attained by balancing bandwidth efficiency versus power efficiency.

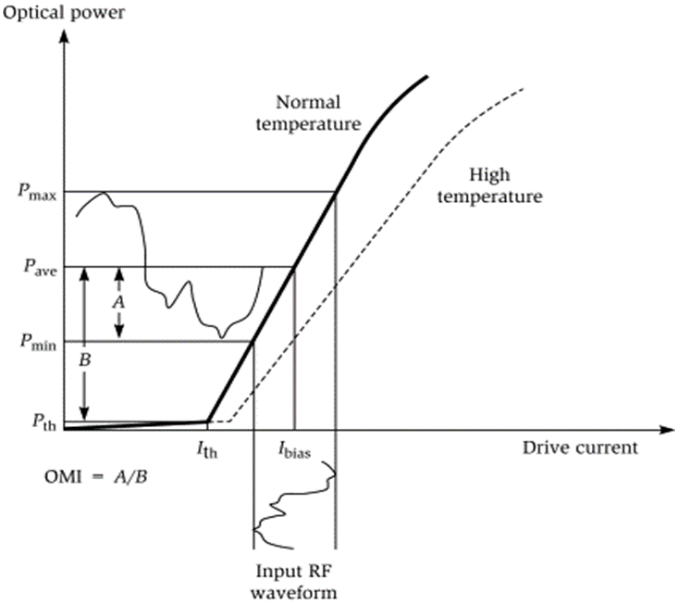

Fig 3: Schematic diagram of the linear mapping between output optical power and input drive current in a typical LED

While the LED is functioning in its linear zone. A photodiode at the receiver makes a proportionate current by immediately detecting variations in light intensity. The simplicity and affordability of IM/DD systems make them popular for use in terrestrial OWC lines. In contrast to simpler systems, coherent systems employ amplitude changes in conjunction with more complex methods like phase or frequency shifts. At the receiving end, a local oscillator helps to combine the incoming signal with a reference signal before it's converted to electricity by a photodetector. While these systems excel in reducing background noise, combating signal weakening due to air disturbances, and picking up fainter signals, their complexity and high power consumption make them less practical for everyday use.

In comparison, Lenses are used in the front-end of Intensity Modulation/Direct Detection (IM/DD) Optical Wireless Communication (OWC) systems to collect and focus the light beam that is received onto a photodiode. With the aid of a trans-impedance circuit, this photodiode functions as a converter, converting the optical signal into an electrical current. The signal is strengthened by this circuit, which typically consists of a resistor and a low-noise optical amplifier. The original information bits are then extracted from the decoded signal by the receiver after it has filtered the output to reduce unwanted noise.

Light-powered Detectors Drive Wireless Communication: Commercial wireless systems that use light (OWC) often rely on special detectors called solid-state photodiodes. These devices excel at converting light into electrical signals, particularly for wavelengths commonly used in OWC. Photodiodes come in different flavors, each with its own strengths. They are all highly responsive to frequently used wavelengths and can react very quickly to changes in light, making them ideal for high-bandwidth applications. Silicon champions: These photodiodes shine around 850 nanometers, a wavelength commonly used for short-range OWC. InGaAs for the long haul: These detectors excel at capturing longer wavelengths, around 1550 nanometers, making them perfect for long-distance OWC. Germanium-rarely seen: While Ge photodiodes can detect a wide range of wavelengths, they are less popular due to a higher level of electrical noise they generate. Avalanche Photodiode (APD) and PIN (Positive-Intrinsic-Negative) are the two primary designs for solid-state photodiodes that may be constructed. PIN diodes: the backbone of outdoor OWC For outdoor wireless communication systems, these dependable photodiodes are frequently utilized, particularly for distances up to a few kilometers. However, their performance can be limited by inherent electrical noise. APDs: reaching new distances: For extremely long-range OWC, Avalanche Photodiodes take the lead. They use a special process to amplify weak light signals, enabling communication over greater distances. This benefit comes with added complexity, though. APDs require a higher voltage to operate, which means more complex circuits and higher power consumption.

4.2. Configuring the Optical Link

Different topologies of optical linkages may be categorized according to two factors, as shown in Figure 4: the presence of a Line-of-Sight (LOS) path and the level of directivity. The data's most obvious path: The strongest signal and fastest transmission are provided via a straight line of sight (LOS) connection between the transmitter and recipient. Without a clear view, signals bounce off ceilings, walls, or other surfaces, creating an indirect (NLOS) environment. However, NLOS connections can be more reliable, maintaining a link even when obstacles block the straight path. Beam focus affects signal strength unlike radio frequency (RF) antennas that broadcast in all directions, optical transceivers have a specific beam angle determined by the light source (LED or laser diode) and receiver field of view (FOV). A directed connection is formed when both sides are small (restricted field of view and tightly concentrated beam). This decreases background light noise, eliminates interference from bouncing signals (multi-path effect), and focuses the signal. For systems that move about, this becomes more complicated since it needs exact positioning and monitoring to maintain the connection. More beams for user convenience: A broad FOV receiver and a wide beam transmitter are used in a non-directed connection. This is easier to use and does away with the requirement for precise alignment—especially for mobile devices. A hybrid connection, which combines a transmitter and receiver with varying degrees of concentration, is an additional alternative.

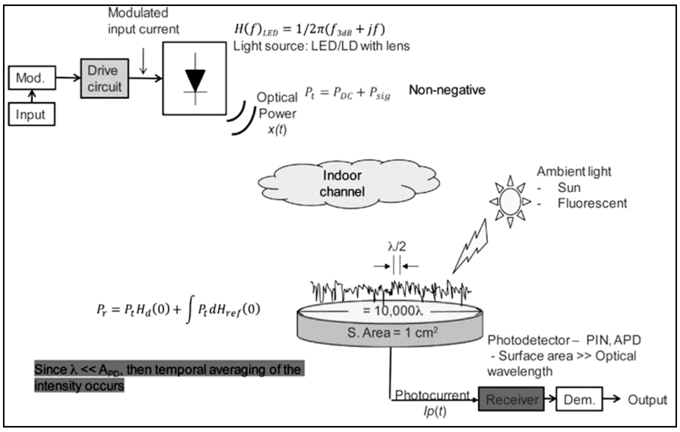

Fig 4: Wireless optical visible light communications links

A high power density is achieved at the receiver in a directed line-of-sight (LOS) link when the transmitter focuses optical energy into a narrow beam. Signal distortion brought on by multipath effects and ambient light interference can be lessened by using a receiver with a narrow field of view (FOV).

More so than multipath dispersion effects, the transmission rate is principally constrained by free-space path loss. As a result, under ideal circumstances, directed LOS lines provide the fastest data speeds and greatest communication ranges. They also enhance security due to the difficulty in intercepting a highly focused optical beam and the susceptibility of eavesdropping attempts to blockage.

Directed LOS technology has been traditionally employed in low-bit-rate applications for simple remote control of household electronics like TVs and audio equipment.

A developing trend in recent years has been the utilization of point-to-point, concentrated communication systems for various outdoor applications. Among these are Wi-Fi networks at universities, building connections, last-mile internet connectivity, and cellular network infrastructure assistance (backhaul and front-haul), connecting things in space (non-terrestrial connectivity), linking satellites, setting up communication after disasters, replacing fiber optic cables in difficult areas, and creating temporary connections.

However, there's a drawback to these systems that rely on a direct line of sight (LOS). They don't work well for covering large areas or allowing users to move around freely. This is due to the fact that communication requires precise alignment between the transmitter and receiver, which makes it challenging to support users who are moving. Additionally, it's challenging to have multiple users using the same system at once with a basic design.

The flexibility of a non-directed line-of-sight (LOS) link makes it a popular choice for indoor communication applications. Wide-beam transmitter and wide-field-of-view (FOV) receiver are used in this arrangement to provide similar mobility to RF systems and wide coverage. By using reflections from inside surfaces, it efficiently reduces blocking and shadowing and makes sure that more transmitted light reaches the photodiode.

Unlike directed LOS links, precise beam alignment and tracking are not critical in non-directed LOS setups. These linkages are prone to multipath-induced dispersion and suffer from substantial attenuation along the optical path. Due to the huge detector sizes compared to the wavelength, multipath propagation does not result in fading; nevertheless, it does introduce inter symbol interference, which reduces data rates.

Moreover, wide-FOV receivers are vulnerable to ambient light interference in well-lit indoor environments, which can degrade link performance significantly.

A diffuse link, sometimes referred to as a non-directed non-line-of-sight (NLOS) optical connection, links a wide-beam transmitter and a wide-field-of-view (FOV) receiver without the need for exact alignment of optical beams. Being impervious to obstruction and shadowing, this arrangement is incredibly resilient and adaptable, which makes it perfect for indoor wireless networks. Unfortunately, across a horizontal distance of 5 meters, it results in severe path loss, usually between 50 and 70 dB. The signal route may be temporarily disrupted by people or furniture, which might result in an additional loss.

Signals that have been multiplexed by reflections from walls, ceilings, and room objects are captured by the broad field of view photodiode of the receiver in a diffuse connection, resulting in considerable signal attenuation, with reflection coefficients generally ranging from 0.4 to 0.9. Furthermore, substantial dispersion-induced inter-symbol interference (ISI), which places restrictions on the highest transmission rate, can be introduced via multipath propagation.

4.3. Optical Wireless Communication Standards

One particularly promising method for communications is visible light communication, or VLC, leveraging the rapid advancement and cost reduction of LED lighting. However, several challenges need addressing:

i). Integration with Existing Standards: VLC systems must seamlessly integrate with established communication standards.
ii). Ambient Light Interference: Dealing effectively with interference from ambient light sources is crucial.
iii). Mobility Considerations: VLC systems need to handle issues like handover smoothly as users move.
iv). Forward Error Correction: It is imperative to have strong forward error correction schemes in order to improve system performance.

Interference between VLC devices becomes a problem as their quantity rises. To solve these issues, the IEEE standard 802.15.7 was created by the Electronic Information Technology Industry Association. This standard aims to:

i). Utilize Terahertz Frequency Bands: Enable access to high-frequency bands for enhanced communication.
ii). Mitigate Electromagnetic Interference: Establish capabilities to counteract electromagnetic interference.
iii). Support Additional Services: Facilitate communication of supplementary services alongside existing visible light equipment.
iv). Specify VLC Communication Parameters: Provide definitions for transmission rates, modulation methods, and forward error correction algorithms.
v). Mechanisms for Channel Access: Provide specific protocols for channel access, such as Contention-Free Periods (CFP) and Contention-Access Periods (CAP), to guarantee effective utilization of the spectrum.
vi). Physical Layer Specifications: Provide information on optical mapping, flicker management, dimming relief, and turnaround times between transmission and reception.

A major advancement in standardizing and expanding the capabilities of VLC technology for wider use is represented by IEEE 802.15.7.

5. Conclusion

For many years, researchers have explored using light for communication. This technology, known by terms like wireless infrared (IR), visible light communication (VLC), wireless ultraviolet (UV) communication, or free-space optical (FSO) communication, shows potential for use in conjunction with existing radio frequency (RF) technologies in the upcoming generation of mobile networks. The Optical Wireless Communication (OWC) can tap into a vast amount of bandwidth across the infrared, visible light, and ultraviolet spectrums. Additionally, it can leverage readily available, inexpensive, lightweight, energy-efficient, and reliable optical sources and detectors-many of which are already commercially available and have long lifespans. The research presented tackles the challenges hindering VLC and proposes solutions to address them. Despite obstacles such blind spots brought on by light spacing and line-of-sight impediments, visible light communication (VLC) has many benefits over traditional radio frequency communication. The development of VLC technology is a major achievement that opens up profitable markets in next-generation optical wireless communication beyond 5G, with potential values surpassing billions of dollars. The advancement of VLC is essential for enabling new domains like as the Internet of Underwater and Underground Things (IoU2T), since it opens doors for creative uses in environmental monitoring, energy management, and connection solutions.

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