International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 09 | Sept - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

A Comprehensive Survey on Wide-Angle Optical Wireless Communication

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Abstract - Optical wireless communication (OWC) has emerged as a vital technology to meet the growing demand for high-speed, secure, and interference-free wireless connectivity. Wide-angle OWC systems extend the communication coverage by utilizing beams with large half power half angles (HPHA) and receivers with broad fields of view (FOV). This comprehensive survey explores the fundamental principles behind HPHA and FOV, their impact on system performance, and the need for optimizing these parameters to balance coverage, signal strength, and robustness. The study reviews techniques to mitigate geometric attenuation and signal distortion challenges inherent in wide-angle propagation, including advanced optical designs such as metasurfaces and lens arrays. Applications spanning from Internet of Things (IoT) and indoor positioning to vehicular and underwater communications are analyzed, highlighting how wide-angle OWC supports flexible, multi-user environments without requiring complex tracking systems. Limitations such as channel attenuation, noise, and interference are discussed along with strategies for system optimization to enhance data rates and reliability. This survey establishes a solid foundation for future research and development of efficient, scalable wide-angle OWC systems tailored to diverse real-world scenarios.

Key Words: Optical wireless communication (OWC), wide-angle transmission, geometric attenuation, energy communication efficiency.

1. INTRODUCTION

Communication is the cornerstone of information exchange, enabling human interaction and the operation of modern systems by transmitting data across distances. Over the decades, communication technology has evolved from wired setups to wireless systems, driven primarily by the demand for mobility, increased capacity, and seamless connectivity. Wireless communication typically utilizes radio frequency (RF) bands to transmit information, and it has become the backbone of global networking infrastructures. However, the explosive growth in devices and data usage has led to congestion and spectrum scarcity in these RF bands, creating a pressing need for alternative wireless communication solutions. Optical Wireless Communication (OWC) has emerged as a powerful candidate to address the limitations of conventional RF communication. OWC transmits data using light waves, including infrared, visible, and ultraviolet spectrums, offering several compelling advantages. It provides access to enormous unregulated bandwidth, capable of supporting ultra-high data rates suitable for next-generation networks. Additionally, OWC is resistant to electromagnetic interference, ensuring more secure and reliable transmission, and offers natural spatial confinement that enhances privacy. Furthermore, OWC technologies like Visible Light Communication (VLC) leverage existing lighting infrastructure, which can simultaneously provide illumination and data services.

Despite these advantages, traditional OWC systems often rely on narrow beamwidths and require precise alignment between transmitters and receivers. This dependency on exact line-of-sight (LOS) paths necessitates the use of costly and complex tracking mechanisms, limiting system scalability and increasing deployment challenges. To overcome these constraints, wide-angle OWC systems have been introduced. These systems utilize transmitters with larger divergence angles (characterized by a higher half power half angle, HPHA) and receivers equipped with broader fields of view (FOV). This design reduces the need for stringent alignment, allows for greater user mobility, and supports multi-user scenarios without complex tracking solutions. The transition n to wide-angle OWC systems brings its own set of challenges. Increasing the HPHA and FOV leads to higher geometric attenuation, reducing signal strength and effective communication range. Additionally, a wider FOV can increase exposure to ambient noise and interference, potentially degrading signal quality. To address these issues, system optimization involving optical components like metasurfaces, lens arrays, and angular diversity arrangements is crucial. These methods enhance spatial coverage while minimizing losses and maintaining robust data transmission capabilities.

Looking ahead, wide-angle OWC systems hold immense promise for expanding wireless connectivity across various applications. These systems are particularly suited for the Internet of Things (IoT), indoor positioning, vehicular communications, underwater communication networks, and beyond 5G wireless systems. Advancements in optical devices, modulation techniques, and channel modeling will continue to improve the performance and reliability of OWC. Additionally, integrating OWC with RF networks into hybrid systems can unlock new levels of connectivity, capacity, and security, driving the future of wireless communication in an increasingly connected world.

Wide-angle optical wireless communication (OWC) systems represent an advanced paradigm in free-space optical networking that eliminates the stringent alignment requirements inherent in conventional narrow-beam configurations by deploying transmitters with large half-power full angles (HPFA) and receivers with expansive fields of view (FOV). These systems fundamentally address the practical limitations of traditional OWC by enabling multi-user access across broad coverage areas without requiring complex tracking mechanisms, though this design approach introduces significant technical challenges including substantial geometric attenuation—where systems with 120° HPFA exhibit channel attenuation differences of approximately 64.4 dB compared to narrow 1 mrad beam systems. The architecture leverages advanced optical techniques such as metasurface-based beam steering, wavelength division multiplexing, and spatial light modulators to achieve wide-angle coverage while maintaining high data transmission rates, with recent implementations demonstrating aggregate capacities exceeding 28 Tbps across 144 parallel channels. However, the expansion of beam divergence necessitates careful management of inter-symbol interference caused by multipath propagation in indoor environments, receiver sensitivity optimization to compensate for reduced signal intensity per unit area, and sophisticated signal processing algorithms to maintain communication quality across the extended coverage zone. Performance evaluation of these systems requires comprehensive analysis of metrics including path loss characteristics, signal-to-noise ratio degradation with increased angular coverage, and bit error rate performance under varying environmental conditions, making wide-angle OWC particularly suitable for applications in high-density indoor networking, vehicle-to-everything communication, and Internet of Things deployments where user mobility and flexible connectivity are paramount.

Traditional optical wireless communication (OWC) systems face numerous critical challenges that significantly limit their practical deployment and operational reliability**.** Strict line-of-sight (LOS) requirements represent the most fundamental limitation, as these systems demand precise alignment between transmitter and receiver, making them highly vulnerable to pointing errors caused by thermal expansion, dynamic wind loads, building sway, mechanical vibrations, and platform mobility. The narrow beam divergence inherent in optical systems, while providing high directional gain, creates severe pointing and tracking difficulties where even minimal misalignment can result in complete signal loss, necessitating complex and expensive acquisition, tracking, and pointing (ATP) mechanisms to maintain communication links. Atmospheric interference poses another major challenge, as optical signals are severely attenuated by weather conditions, including fog (which can cause attenuation up to 350 dB/km in dense conditions), rain, snow, and atmospheric turbulence that induces scintillation effects leading to signal amplitude and phase fluctuations. The systems suffer from limited transmission range due to eye and skin safety regulations that restrict maximum permissible transmitter power, confining effective operation to distances of only a few meters in indoor environments and preventing signal penetration through solid barriers like walls. Multipath dispersion in indoor environments creates significant performance degradation, as optical signals reflecting off walls, ceilings, and furniture arrive at receivers at different times, causing intersymbol interference (ISI) that limits achievable data rates and degrades signal quality. Additionally, traditional OWC systems face device bandwidth limitations, where typical LED transmitters are restricted to tens or hundreds of MHz, limiting single-device data rates to below 10 Gbps despite the vast optical spectrum availability, while atmospheric turbulence causes beam wandering and signal fluctuations that require sophisticated compensation techniques. These fundamental challenges collectively restrict traditional OWC systems to specialized point-to-point applications with controlled environments, limiting their scalability and widespread adoption in mobile or dynamic communication scenarios.

2. LITERATURE SURVEY

Optical wireless communication (OWC) has gained significant attention in recent years as a complementary technology to conventional radio frequency (RF) systems, motivated by the demand for higher bandwidth, immunity to electromagnetic interference, and the potential for low-cost implementation. The literature presents diverse approaches to addressing the inherent challenges of OWC, particularly alignment dependence, attenuation, and system robustness.

Zhou *et al.* [1] introduced one of the most comprehensive explorations of wide-angle OWC systems, focusing on the design and prototyping of systems based on infrared VCSELs and blue LEDs. Their work demonstrated the feasibility of long-distance, tracking-free communication, with distances of up to 2.61 km achieved at moderate data rates. Importantly, they also proposed novel methods for estimating peak optical power and introduced the concept of *energy communication efficiency* as a new metric for fair comparison across OWC designs. This study provides the foundation for wide-angle, alignment-free communication systems.

In contrast, Sun *et al.* [2] addressed the limitations of misalignment through high-precision tracking systems for free-space optical communication (FSO). Their work focused on mobile platforms where maintaining a stable optical link is particularly challenging. By integrating advanced tracking and stabilization mechanisms, they were able to preserve high-quality links even under mobility. While effective, such approaches come at the cost of complexity and hardware expense, highlighting the trade-off between robustness and system cost.

Another line of research combines optical and radio frequency systems. Rakia *et al.* [3] proposed an optimal design for a dual-hop VLC/RF system with energy harvesting capabilities. Their work demonstrated how hybrid systems can overcome individual limitations of VLC (limited coverage, alignment sensitivity) and RF (spectrum congestion) while simultaneously enhancing energy efficiency. This direction shows promise for sustainable communication systems but requires more complex integration of heterogeneous technologies.

OWC is also actively researched for underwater environments, where RF and acoustic methods are constrained. Zhou *et al.* [4] demonstrated a real-time underwater OWC system achieving communication over distances exceeding 50 meters. Using blue-green light optimized for underwater propagation, their system balanced attenuation and scattering to enable reliable links in challenging aquatic conditions. This work highlights the adaptability of OWC to domains where conventional wireless technologies fail.

In terms of high-data-rate systems, Ali *et al.* [5] demonstrated gigabit transmission between an eye-safe transmitter and a wide field-of-view (FOV) silicon photomultiplier (SiPM) receiver. Their results emphasize that high sensitivity receivers with wide FOVs can enable both high capacity and robust coverage, bridging the gap between narrow-beam, high-performance systems and wide-angle, misalignment-tolerant designs.

Beyond these works, several other studies enrich the OWC literature. Weng *et al.* (2024) provided a comprehensive review of indoor OWC systems, highlighting challenges such as ambient light interference, mobility, and receiver FOV limitations. Similarly, Jenila and Jeyachitra (2024) investigated energy-efficient OWC-IoT systems, proposing the use of passive reflective filters and machine learning–based quality prediction to optimize system design. In the domain of advanced device integration, Wang *et al.* (2025) explored the use of metasurfaces for beam shaping and intelligent control in OWC, demonstrating their potential to dynamically manage divergence and directionality.

From these studies, a clear picture emerges: while traditional OWC systems excel in high-performance scenarios, they suffer from alignment and cost limitations. Tracking-based solutions [2] can mitigate these issues but add complexity, while hybrid VLC/RF systems [3] offer reliability at the expense of integration challenges. Wide-angle systems [1][5], underwater applications [4], and novel device technologies provide promising directions for future development. Collectively, the literature underscores the importance of balancing divergence, FOV, and energy efficiency to realize practical, scalable, and application-specific OWC systems.

Weng *et al.* [6] provided a comprehensive review of indoor OWC systems, discussing both the opportunities and challenges in confined environments such as offices, hospitals, and shopping malls. Their analysis highlighted key issues like ambient light interference, user mobility, and receiver field-of-view limitations. They also surveyed mitigation strategies, including advanced modulation schemes, optical filtering, and system-level design approaches, making this work a valuable reference for researchers focusing on indoor OWC deployment.

Jenila and Jeyachitra [7] focused on the integration of OWC into energy-efficient IoT systems. They proposed the use of passive reflective filters to improve optical signal collection and employed machine learning algorithms to predict link quality dynamically. Their study demonstrated that OWC can be adapted for sustainable IoT applications, where power efficiency and scalability are critical design factors.

Wang *et al.* [8] explored the application of metasurfaces in OWC. Unlike conventional optics, metasurfaces can dynamically control the phase, amplitude, and direction of light at subwavelength scales, enabling intelligent beam steering without bulky mechanical tracking systems. Their work showed the potential for compact, adaptive OWC architectures that can respond to changing environmental or user conditions in real time, marking a major step toward intelligent optical communication systems.

Armghan *et al.* [9] investigated a hybrid underwater OWC/UWB communication system designed for wireless sensor networks. Their approach leveraged the high bandwidth of optical links while combining it with ultra-wideband RF to ensure robustness in challenging underwater environments. The proposed system achieved scalable performance, suggesting a practical solution for underwater IoT and sensor monitoring applications where single-technology systems face significant limitations.

3. APPLICATION AREAS OF WIDE-ANGLE OWC

Wide-angle optical wireless communication (OWC) systems are attractive because they eliminate the need for expensive and complex tracking mechanisms while maintaining robust connectivity. This makes them highly versatile across several application domains:

a) Internet of Things (IoT): Wide-angle OWC can serve as a low-cost and energy-efficient backhaul for IoT devices deployed in smart homes, factories, or cities. Since these devices are often small, mobile, and randomly positioned, alignment-free wide-angle links enable seamless connectivity without the need for precise positioning.

b) Vehicular Networks (Internet of Vehicles): In intelligent transportation systems, vehicles require high-speed, low-latency communication with road infrastructure and other vehicles. Wide-angle OWC allows data exchange without strict alignment, making it suitable for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) links where mobility and dynamic environments are major challenges.

c)Indoor Positioning and Networking: In indoor environments such as offices, hospitals, or shopping malls, wide-angle OWC can be used for both communication and localization. Light-based links are immune to electromagnetic interference, making them ideal for sensitive areas such as hospitals or factories with heavy machinery. Moreover, wide-angle coverage ensures reliable links even when users move frequently within a room.

d) Underwater Communication: Radio frequency (RF) signals attenuate rapidly in water, and acoustic communication suffers from low bandwidth and high latency. Wide-angle OWC using blue or green light provides a promising alternative for short- to medium-range underwater communication, supporting applications such as diver-to-diver links, underwater drones, and marine sensor networks.

e) Temporary and Emergency Networks: Wide-angle OWC can also be deployed in disaster recovery or temporary event networks where infrastructure is limited. Since wide divergence beams do not require strict alignment, such systems can be set up quickly and at lower cost than conventional free-space optical systems.

4. CONCLUSIONS

Wide-angle optical wireless communication (OWC) systems provide a practical and robust alternative to traditional narrow-beam, tracking-based systems by eliminating the need for complex alignment mechanisms. By optimizing the half power half angle (HPHA) of transmission and the field of view (FOV) of reception, these systems achieve broad coverage and flexible connectivity, supporting dynamic and mobile scenarios with multiple users. Although wider angles introduce challenges such as increased geometric attenuation, reduced signal strength, and susceptibility to noise and interference, advancements in optical components and design strategies like metasurfaces and lens arrays help mitigate these issues. The capability to maintain reliable kilometer-scale communication without expensive tracking equipment demonstrates the feasibility of wide-angle OWC for applications including IoT, vehicular networking, indoor positioning, and underwater communication. Therefore, wide-angle OWC stands as a promising technology for future wireless networks, enabling high-capacity, energy-efficient, and scalable communication that addresses the growing demands for mobility and flexibility in diverse environments.

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