Proceedings of CONF-FMCE 2025 Symposium: Semantic Communication for Media Compression and Transmission
DOI: 10.54254/2755-2721/2025.GL25927

Research on Anti-Fading Technology of Underwater Wireless Optical Communication Based on Fading Models

Xinyi Guo

Xinglin College, Nantong University, Nantong, China
gggxinyi@outlook.com

Abstract. With the country's increasing emphasis on the survey and development of marine resources and military applications, the further advancement of underwater wireless optical communication(UWOC), as a pivotal technology to support the efficient transmission of marine information, has become an imminent hot topic. To address the performance issues of reducing the error rate of UWOC system and improving the system's transmission performance, this article studied various anti-fading technologies which based on different fading models, such as log-normal ones applicable to weak underwater turbulence and Gamma-Gamma types suited for strong underwater turbulence, corresponding to the two turbulence scenarios respectively, exploring their practical effects in signal transmission. Also, it analyzed the current problems and challenges of fading models and anti-fading technologies from various perspectives, such as underwater complex environment, channel conditions and hardware cost. Accordingly, it proposed the research directions and prospects for the future in choosing reasonable fading models in specific application scenarios and enhancing the anti-fading technologies through technological innovation.

Keywords: underwater wireless optical communication system, anti-fading technology, fading models

1. Introduction

With the increasing frequency of activities such as the development of marine resources and military applications, people's requirements for underwater communication are also getting higher and higher. Unlike conventional hydroacoustic communication methods and underwater radio frequency(RF) communication means, underwater wireless optical communication(UWOC) has received the attention of the majority of scholars owing to its merits, including high-rate data transmission capability, high local confidentiality performance, and low cost of equipment [1]. However, light waves are affected by absorption, scattering, and turbulence during transmission, leading to signal attenuation, fading, etc., which reduces the quality of the beam, of which absorption and scattering have been more comprehensively studied both at home and abroad, but have not yet been well characterized in terms of coping with turbulence-induced fading.

This paper aims to investigate various types of UWOC anti-fading techniques based on the fading model, so as to advance the UWOC system's functional performance. To begin with, the research background and purpose of the paper are stated, pointing out the current challenges of UWOC and

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2025.GL25927

the research focus of this paper. Next, the factors affecting UWOC and the role of UWOC anti-fading techniques are briefly introduced. In addition, the commonly used fading models for weak turbulence and their signal transmission characteristics are described, and the anti-fading techniques to reduce the BER under weak turbulence in recent years are introduced, and some future challenges and research directions of these techniques are analyzed. Furthermore, this paper introduces the fading model and its transmission characteristics for strong turbulence, clarifies how underwater strong turbulence affects optical signals, and briefly describes several anti-fading techniques that can effectively reduce the BER of the system, as well as the direction of future improvement of these techniques. Finally, the main research contents are summarized, and the future prospects of UWOC research are put forward from the aspects of anti-fading technology and underwater simulation environment.

2. Introduction to anti-deterioration technology

Underwater wireless optical communication is susceptible to absorption, scattering, and turbulence, which greatly reduces the distance and energy of light waves transmitted underwater. For UWOC to be more widely used in ocean exploration, resource extraction, military applications and other aspects, advanced and efficient anti-fading technology is needed to enhance the effectiveness and dependability of UWOC systems during optical signal transmission.

Anti-fading techniques can not only resist signal attenuation and suppress signal fluctuations caused by turbulence by optimizing the wavelength and optical source power, but also enhance the robustness of the UWOC system by using diversity, modulation and coding. The current anti-fading technology is also making breakthroughs in the dimensions of channel compensation, modulation coding, and multi-domain synergy. In terms of channel compensation technology, such as aperture averaging technology is used to suppress light intensity scintillation; at the level of modulation coding, there are orthogonal frequency division multiplexing, and polarization codes to improve the reliability of the system; Multi-domain synergy techniques, on the other hand, enhance the robustness of the system through various types of diversity techniques. The intensity of underwater turbulence changes from weak to strong depending on factors such as temperature, salinity, and current motion, and this change has a significant effect on the decay characteristics of the optical signal. Therefore, it is crucial to select reasonable fading models as well as anti-fading techniques for different turbulence conditions.

3. Anti-fading techniques under weak turbulence

3.1. Signal transmission characteristics under weak turbulence

Under weak turbulence conditions, the light intensity undulation usually obeys models such as the lognormal distribution(LN), when the signal decay is relatively flat, and the signal undulation can be suppressed by basic modulation techniques, aperture averaging, and diversity techniques.

The LN model was first used for free-space optical communications and is a classical model for studying weak atmospheric turbulence. The LN model originates from the first-order Rytov approximation. The function curve of the distribution models the fading of the channel better when describing underwater weak turbulence, but the LN model is not well applicable when strong turbulence is present. After extensive experimental measurements and validation, the probability density function of the LN is [2]:

DOI: 10.54254/2755-2721/2025.GL25927

$$f_h(h) = \frac{1}{h\sqrt{2\pi\sigma_l^2}} \exp\left(-\frac{\left(\ln(h/h_l)+\frac{1}{2}\sigma_l^2\right)^2}{2\sigma_l^2}\right) \tag{1}$$

3.2. Research on anti-fading techniques under weak turbulence

Some progress has been made in anti-fading techniques for UWOC under conditions of weak turbulence, and these techniques can be based on the Weibull distribution model and the exponential-logarithmic distribution model, in addition to relying on the most commonly used LN model for the performance of UWOC systems. Moreover, although the attenuation of optical signals caused by weak turbulence is relatively small, the channel fading caused by it cannot be ignored. At present, under weak turbulence conditions, some anti-fading techniques such as multiple-input multiple-output(MIMO), polarization modulation, spatial diversity, etc., can improve the system's interference immunity and transmission performance to a certain extent.

For the UWOC system under a weak turbulence environment, to improve its performance, S.Alireza Nezamalhosseini et al. used MIMO technique based on the LN model and combined it with an optimal power assignment strategy at the transmitting end. This approach not only effectively reduces the systems' BER but also enhances performance in comparison to schemes like equal power allocation [3]. Yatong Song et al. significantly reduced the ABER of the system by adopting an anti-fading technique based on a composite log-normal fading model using a partially coherent beam(PCB) combined with a polarization code. At the same BER, the PCB system with a polarization code achieves a signal-to-noise ratio(SNR) improvement of about 11 dB as opposed to the non-coded system, and the larger spatial coherence of the beam helps to further performance improvements [4]. Manh Le-Tran et al. used a multi-hop relaying technique based on a hybrid EGG distribution combined with anti-fading techniques such as a heterodyne detector and a direct detector, which reduces the probability of interruption and average BER. These techniques improve the system reliability and communication performance under a weak turbulence environment [5]. Wei Wang et al. used POV beams combined with spatial pattern modulation and multiplexing techniques based on the hybrid Gamma-Gamma and normal distribution models, utilizing the independent radial distribution characteristics of POV beams' topological charge to reduce the pattern crosstalk induced by turbulence, reduce the system's BER, improves the channel capacity, and enhance the system's reliability and transmission effciency [6].

3.3. Challenges and future research directions

UWOC has made some breakthroughs in weak turbulence anti-fading technology, which have effectively improved the performance of the system, but there are still challenges in the adaptation to the underwater dynamic environment, the complexity of the channel, as well as the limitations of the hardware and the cost of the issues, biological activities in the water body, bubbles, turbidity changes can exacerbate the signal attenuation, and some high-performance light sources as well as high-sensitivity detectors, etc., are also limited by the underwater absorption and some high-performance light sources and high-sensitivity detectors are also limited by underwater absorption and scattering, which can significantly reduce the transmission distance. In addition, for the reduction of the system BER problem subsequent can also be considered in conjunction with the new underwater turbulence model and combined with MIMO, convolutional neural networks and other technologies to carry out research, but like the MIMO technology to enhance the system's

DOI: 10.54254/2755-2721/2025.GL25927

dependability at the same time also increases the cost of the hardware, so the future in the study of anti-fading technology performance and practicality still need to make some trade-offs between.

4. Anti-fading techniques under strong turbulence

4.1. Signal transmission characteristics under strong turbulence

Under moderately turbulent as well as strongly turbulent conditions, the light intensity fluctuation usually obeys models like the generalized gamma distribution and Gamma-Gamma distribution model, at which time the signal fading becomes drastic, and techniques such as spatial diversity and adaptive optics need to be introduced to overcome the problems of signal fading and communcation interruption.

Unlike the LN model, the generalized gamma distribution is applied to underwater turbulence ups and downs from weak to strong, and its probability density function is as follows [2]:

$$f_R(r) = \frac{2v}{(\Omega/m)^m \Gamma(m)} r^{2vm-1} \exp\left(-\frac{mr^{2v}}{\Omega}\right), r > 0 \tag{2}$$

4.2. Research on anti-fading techniques under strong turbulence

Underwater stong turbulence will make the refractive index of the water body undergoes a huge change, resulting in the optical signal in the transmission process by refraction and scattering, thus causing the beam shift phenomenon. Secondly, strong turbulence will also produce eddies and perturbations, so that the intensity of the optical signal undergoes a rapid change, i.e., the light intensity scintillation phenomenon; In addition, strong turbulence causes beam expansion and deformation, making the beam unfocused and the light energy dispersed, and the light intensity arriving at the receiving end is weakened, which reduces the quality of the UWOC and can seriously lead to interruption of communication. Many advanced anti-fading techniques based on the generalized gamma distribution model have been used to improve parameters such as outage probability, BER of the system, and channel capacity under strong turbulence conditions.

To improve the performance of the UWOC under strong turbulence, Sravan Kumar Padala et al.used spatially coupled low-density parity-check codes as an anti-fading technique based on the Gamma-Gamma distribution model, which effectively enhances the BER characteristics of a UWOC system when faced with strong turbulence and errors in pointing, while reducing the decoding complexity and delay [7]. Arvind Kumar et al. effectively reduced the system's average BER based on the EGG distribution model by using a selective combining diversity technique in multi-aperture systems combined with switching-keying and incoherent intensity modulation/direct detection schemes. And the system performance is improved by augmenting the quantity of apertures [8]. Ankur Bansal et al. used Selective Combining(SC) and Maximum Ratio Combining(MRC) diversity techniques in multi-aperture systems and grounded in the Hybrid EGG distribution model to acquire signals through multiple receiving apertures and combine them, where SC selects the optimal signal-to-noise-ratio signals, and MRC selects the weighted combined signals, which effectively improved the reliability of UWOC systems under strong turbulence and pointing error [9]. Yuqing Fu et al. employed rectangular QAM technique based on the Gamma-Gamma distribution model, while using the aperture average effect and optimizing the system parameters to combat fading. These techniques reduce the system's average BER and significantly enhance the operational reliability of UWOC systems in strong turbulence environments [10].

4.3. Challenges and future research directions

Currently, there are a variety of anti-fading techniques in strong turbulence environments to correct errors in transmission by adding redundant information, effectively improving the performance of the system, such as LDPC coding techniques. At the same time, signal processing techniques such as OFDM have also been used to improve the system's ability to resist fading; In addtion, there are several applications of high beam quality light sources and the introduction of advanced technologies such as MIMO, all of which effectively improve the system's performance. However, under conditions of strong turbulence, there are still problems and challenges such as beam shift, light intensity flicker, etc., which may impact the reliability of the system and are difficult to be completely eliminated, and the adaptability of the current anti-decay technology in the complex water environment still needs to be strengthened, so in the future, we can continue to optimize the technologies such as adaptive optics, and apply some efficient anti-decay algorithms as well as new anti-decay materials to the existing technologies, so that we can construct a more stable UWOC system from the improvement of system parameters and other aspects to build a more stable UWOC system.

5. Conclusion

In this paper, fading model-based anti-fading techniques for underwater wireless optical communications are investigated, demonstrating the research progress in effectively improving the system performance by different anti-fading techniques under weak and strong turbulence conditions. The applicability of UWOC in long-distance underwater communication is not yet high, if we want to make its current long-distance communication reliable and flexible, we can consider combining the hydroacoustic communication technology while researching UWOC in the future, because the communication distance and range of acoustic wave underwater is very wide, so we can make up for the short board of the UWOC through the advantage of acoustic wave, but we should pay attention to its impact on underwater organisms and the environment when combining the optical communication with acoustic communication. However, while combining optical communication with acoustic communication, attention should also be paid to its impact on underwater organisms and the environment. In addition, fading models provide a theoretical basis for studying UWOC signal attenuation and fluctuation. Therefore, the adoption of a fading model that can comprehensively simulate the ups and downs of weak-to-strong underwater turbulence is crucial for studying the performance of UWOC systems. Further, the development of more efficient and low-cost anti-fading techniques and conducting experiments in complex waters are also important research directions for UWOC.

References

[1] S. J. Zhu, X. W. Chen, X. Y. Liu, G. Q. Zhang, P. F. Tian, Recent progress in and perspectives of underwater wireless optical communication, Progress in Quantum Electronics, Volume 73, 2020, 100274, ISSN 0079-6727

[2] Y. Ata and K. Kiasaleh, "Analysis of Optical Wireless Communication Links in Turbulent Underwater Channels With Wide Range of Water Parameters, " in IEEE Transactions on Vehicular Technology, vol. 72, no. 5, pp. 6363-6374, May 2023.

[3] S. A. Nezamalhosseini and L. R. Chen, "Optimal Power Allocation for MIMO Underwater Wireless Optical Communication Systems Using Channel State Information at the Transmitter, " in IEEE Journal of Oceanic Engineering, vol. 46, no. 1, pp. 319-325, Jan. 2021.

[4] Y. Song, P. Wang, S. Li, G. Li, W. Pang and S. Gu, "Performance analysis of polar-coded underwater wireless optical communication systems with partially coherent beams, " 2022 IEEE 8th International Conference on

DOI: 10.54254/2755-2721/2025.GL25927

Computer and Communications (ICCC), Chengdu, China, 2022, pp. 230-235.
[5] M. Le-Tran and S. Kim, "Performance Analysis of Multi-Hop Underwater Wireless Optical Communication Systems Over Exponential-Generalized Gamma Turbulence Channels, " in IEEE Transactions on Vehicular Technology, vol. 71, no. 6, pp. 6214-6227, June 2022.
[6] W. Wang, P. Wang, W. Pang, Y. Pan, Y. Nie and L. Guo, "Evolution Properties and Spatial-Mode UWOC Performances of the Perfect Vortex Beam Subject to Oceanic Turbulence, " in IEEE Transactions on Communications, vol. 69, no. 11, pp. 7647-7658, Nov. 2021.
[7] S. K. Padala and J. D’souza, "Performance of Spatially Coupled LDPC Codes Over the Underwater Wireless Optical Channel With Strong Turbulence and Pointing Errors, " in IEEE Access, vol. 12, pp. 58256-58274, 2024.
[8] A. Kumar, S. M. Husain, P. Sial and S. M. Zafaruddin, "Exact Performance Analysis for Multi-Aperture UWOC Systems Over EGG Oceanic Turbulence, " 2024 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom), Tbilisi, Georgia, 2024, pp. 159-164.
[9] A. Bansal, Z. Rahman and S. M. Zafaruddin, "Diversity Analysis of Multi-Aperture UWOC System Over EGG Channel With Pointing Errors, " in IEEE Communications Letters, vol. 27, no. 8, pp. 2073-2077, Aug. 2023.
[10] Y. Q. Fu, Q. Duan, C. T. Huang, Y. Z. Du, L. Zhou, Average BER performance of rectangular QAM-UWOC over strong oceanic turbulence channels with pointing error, Optics Communications, Volume 476, 2020, 126362, ISSN 0030-4018