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Review TOEOC

Optimized Receivers for Underwater Visible Light Communication

B. Vijayalakshmi[1,*], G. Hema Likhita[2], G. Meghana[3], G. Meghana[4], B. Jeevana Jyothi[5]

Abstract

Wireless communication underwater is crucial for uses like ocean exploration, environmental monitoring, and underwater data transfer, wireless communication under water is crucial. Conventional acoustic and radio frequency communication methods suffer from low bandwidth, high latency, and severe signal attenuation in underwater environments. With its high data rate and low propagation delay, visible light communication (VLC) provides a promising alternative. In this work, an underwater VLC system is implemented using light-emitting diodes (LEDs) with intensity modulation and on–off keying (OOK). The underwater optical channel is modeled considering absorption, scattering, and turbulence effects influencing signal propagation. A single-photon avalanche diode (SPAD) receiver is used for photon-counting detection under low-light conditions. To enhance detection performance, advanced techniques such as threshold detection, multiple symbol detection (MSD), and generalized likelihood block detection (GLBD) are implemented. Furthermore, block coding and fast search algorithms are applied to reduce bit error rate (BER) and computational complexity. Simulation results demonstrate improved BER performance under different signal-to-noise ratio (SNR), optical power, and turbulence conditions, highlighting the effectiveness of the proposed system for reliable underwater communication. The system undergoes evaluation using different water types and attenuation coefficients to simulate actual ocean conditions. Furthermore, the suggested method shows resilience to background noise and alignment problems, thereby guaranteeing stable communication links.

Keywords: Underwater visible light communication, optical wireless communication, SPAD receiver, MSD, GLBD, OOK modulation, BER performance

INTRODUCTION

Underwater wireless communication is crucial for ocean exploration and environmental monitoring. Conventional acoustic and radio frequency (RF) systems suffer from low bandwidth, high latency, and severe signal attenuation in underwater environments, which limit high-speed data transmission [1, 2]. Visible Light Communication (VLC) has emerged as a promising alternative for short-range underwater communication because of its high bandwidth and low propagation delay. VLC systems employ light-emitting diodes (LEDs) for transmission and optical receivers using on–off keying (OOK) modulation. However, underwater optical signals are affected by absorption and scattering, which degrade their performance [3, 4]. Single-photon avalanche diode (SPAD) receivers with photon-counting capabilities were used to enhance detection under weak optical conditions.

*Author for Correspondence
B. Vijayalakshmi
E-mail: vhans2011@gmail.com

1Associate Professor, Department of Electronics and Communication Engineering, Gayatri Vidya Parishad College of Engineering for Women Visakhapatnam, Andhra Pradesh, India
[2-5]Student, Department of Electronics and Communication Engineering, Gayatri Vidya Parishad College of Engineering for Women Visakhapatnam, Andhra Pradesh, India

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Generalized likelihood block detection (GLBD) enables blind signal detection without prior channel knowledge while improving the bit error rate (BER) performance and reducing the computational complexity, making VLC suitable for reliable underwater communication [5, 6]. Additionally, VLC offers several advantages, such as low power consumption, high security, and immunity to electromagnetic interference. Compared with acoustic communication systems, VLC provides a significantly higher bandwidth, making it suitable for real-time underwater applications such as video transmission, sensor networks, and underwater robotics [7, 8]. Furthermore, VLC enables faster data transmission with reduced latency, which is essential for time-critical applications such as autonomous driving. However, maintaining proper alignment between the transmitter and receiver remains a challenge in practical underwater environments owing to movement and water turbulence.

In addition to basic Ultraviolet C (UVLC) system implementation, this study also focuses on improving system performance using advanced detection techniques such as GLBD and MSD. The performance of the system was further analyzed under different underwater turbulence conditions (0.1, 0.3, and 0.6). Furthermore, techniques such as block coding and fast search algorithms are implemented to reduce the BER and computational complexity. This makes the proposed system more robust and efficient for practical underwater communication applications [9].

LITERATURE REVIEW

The impact of underwater channel impairments, such as turbulence and background radiation, on photon-counting receivers was analyzed [10]. The study modeled the SPAD detection process by considering dead time effects, showing that practical photon-counting statistics deviate from ideal Poisson behavior. The proposed GLBD receiver jointly estimates the system parameters and transmitted data sequences, enabling reliable detection even without prior channel knowledge. The simulation results confirmed that the proposed method approaches the BER lower bound while maintaining reduced computational complexity.

A fast search algorithm was introduced to enhance the efficiency of the GLBD receiver. The algorithm reduces the search space required for sequence detection, lowering the computational complexity compared with exhaustive search methods. Performance evaluation demonstrated that the fast algorithm maintains detection accuracy while significantly improving processing efficiency, making it suitable for practical underwater VLC implementation.

This study also highlights the importance of advanced detection techniques, such as the GLBD and MSD, in improving BER performance under practical underwater conditions, including turbulence and noise.

An underwater optical wireless communication model describing the transmitter, channel, and receiver components was discussed [11]. The study emphasized that optical communication provides higher data rates than acoustic communication, especially for short-range applications. The authors also analyzed the influence of absorption and scattering coefficients for different water types, highlighting how environmental conditions affect signal attenuation and the overall system performance.

The study further compared acoustic and optical underwater communication techniques, concluding that optical communication offers lower propagation delay and higher bandwidth, although it requires proper alignment between the transmitter and receiver [12, 13]. This study demonstrated the potential of VLC systems as an efficient solution for high-speed underwater data transmission, despite environmental challenges.

This study also highlighted the importance of photon-counting receivers in improving the detection sensitivity under low-light conditions. Furthermore, it emphasizes the need for efficient signal processing algorithms to handle underwater channel uncertainties and improve overall system performance [14, 15].

PROPOSED SYSTEM

The proposed system, as shown in Figure 1, is based on an underwater VLC framework designed for reliable short-range optical wireless communication. The system consists of a transmitter, underwater optical channel, and receiver. At the transmitter, electrical information signals are converted into optical signals using an LED. On–off keying (OOK) is used for intensity modulation, with the presence of light indicating binary '1' and the absence of light indicating binary '0.' This modulation scheme was chosen because of its simplicity and suitability for optical communication systems.

The transmitted OOK signal can be mathematically represented as:

$$s(t) = A \times b(t)$$

where, A represents the amplitude of the optical signal, and b(t) denotes the binary data sequence (0 or 1).

The SPAD receiver detects incoming photons using a probabilistic model. The photon detection process follows a Poisson distribution, given by

$$P(k) = (\lambda^k e^{-\lambda}) / k!$$

where λ represents the average photon arrival rate, and k denotes the number of detected photons during a given interval. This statistical model helps accurately analyze signal detection under noisy underwater conditions.

The transmitted optical signal propagates through the underwater channel, where signal degradation occurs owing to the absorption and scattering effects caused by water particles. These effects introduce attenuation and turbulence, influencing communication performance depending on the water conditions and transmission distance.

At the receiver, a SPAD is used for photon-counting detection. Unlike conventional photodiodes, SPAD receivers detect individual photons, enabling improved sensitivity under weak optical signals. The received photon counts are affected by background noise and detector dead time, which makes accurate signal detection challenging.

In addition to basic signal detection, advanced detection techniques such as threshold detection, MSD, and GLBD are incorporated into the system. The GLBD performs blind detection without requiring prior channel knowledge and provides superior BER performance under turbulence conditions. The MSD improves the detection accuracy by considering the symbol sequences but increases the computational complexity. To further enhance the system performance, block coding was used to reduce the error rates, and a fast search algorithm was implemented to reduce the computational complexity while maintaining the detection accuracy.

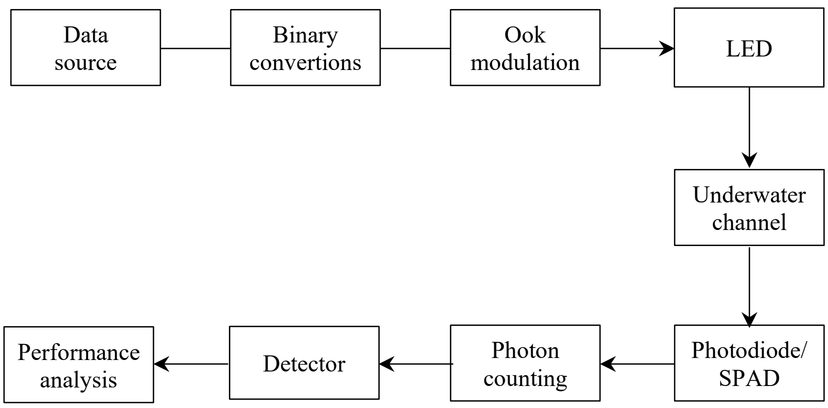

Figure 1. Block diagram.

To address these challenges, GLBD is employed as a blind detection technique. The GLBD estimates transmitted data sequences without requiring prior channel state information and reduces the computational complexity using a fast search algorithm. Compared to conventional detection methods, the proposed approach improves the BER performance and enhances robustness in underwater environments. The overall system enables efficient and reliable underwater optical communication using VLC.

Detection Techniques

In SPAD-based UVLC systems, accurate signal detection is essential because of the presence of noise, turbulence, and attenuation. Different detection techniques were used to improve performance.

Threshold Detection

A simple method in which photon counts are compared with a threshold value to detect transmitted bits. It has low complexity but performs poorly under noise.

Multiple Symbol Detection

MSD considers multiple symbols for detection, improving accuracy but increasing computational complexity.

Generalized Likelihood-Based Detection

GLBD is a blind detection technique that does not require prior knowledge of the channel. It provides the best BER performance and is robust under turbulent conditions.

Block Coding

Used to reduce BER and eliminate the error floor by processing data in blocks.

Fast Search Algorithm

It reduces the computational complexity of the GLBD by limiting the search space, making the system more efficient.

BLOCK DIAGRAM

The proposed underwater VLC system consists of transmitter, channel, and receiver stages designed for reliable optical data transmission.

At the transmitter side, the data source generates an input information signal (audio or digital data). The binary conversion block initially converts this signal into a binary sequence that represents the information as a series of 0s and 1s. On–off keying (OOK) modulation is then applied to the binary data, where a light presence signifies a binary ‘1’ and a light absence signifies a binary ‘0.’

The modulated electrical signal drives an LED, which converts the electrical signal into an optical signal. The emitted light propagates through the underwater channel, where signal degradation occurs owing to the absorption and scattering effects caused by water particles and environmental conditions.
At the receiver side, the incoming optical signal is detected using a photodiode or SPAD**.** The SPAD performs photon-counting, enabling reliable detection even under weak light conditions. The detected signal is then passed to the detector block, where the received optical signal is demodulated and converted back into digital data.

Finally, performance analysis is conducted to evaluate the system performance using parameters such as BER and signal reliability. This overall process enables efficient underwater optical communication using VLC.

RESULTS

The relationship between the BER and signal-to-noise ratio (SNR) for the underwater VLC system is depicted in the upper graph of Figure 2. As the SNR increases, the BER decreases, which signifies enhanced communication reliability when the noise level is reduced. This demonstrates that a higher signal strength results in more accurate data detection. The lower graph represents the received electrical signal after transmission through the noisy underwater channel. The fluctuations in the signal illustrate the effects of underwater noise and channel disturbances on the received data.

This result clearly indicates that the proposed SPAD-based system outperforms conventional photodiode receivers, particularly under low-signal conditions. The improvement in the BER demonstrates the effectiveness of photon-counting detection in underwater VLC systems.

Figure 3 illustrates the photon counts detected by the SPAD receiver at different sample indices. The number of photons received in a given sampling interval is represented by the spikes. Variations in photon counts occur because of channel noise and underwater attenuation effects. The results demonstrate the photon-counting capability of the SPAD receiver for detecting weak optical signals in underwater VLC systems.

The upper plot in Figure 4 illustrates how the BER changes in relation to the SNR for the underwater VLC system. As the SNR increases, the BER decreases, indicating improved communication reliability under reduced noise conditions. This behavior confirms better signal detection at higher signal strengths. The lower plot represents the received electrical signal after transmission through the noisy underwater channel. The fluctuations in the signal demonstrate the effects of underwater noise and channel attenuation on the received data.

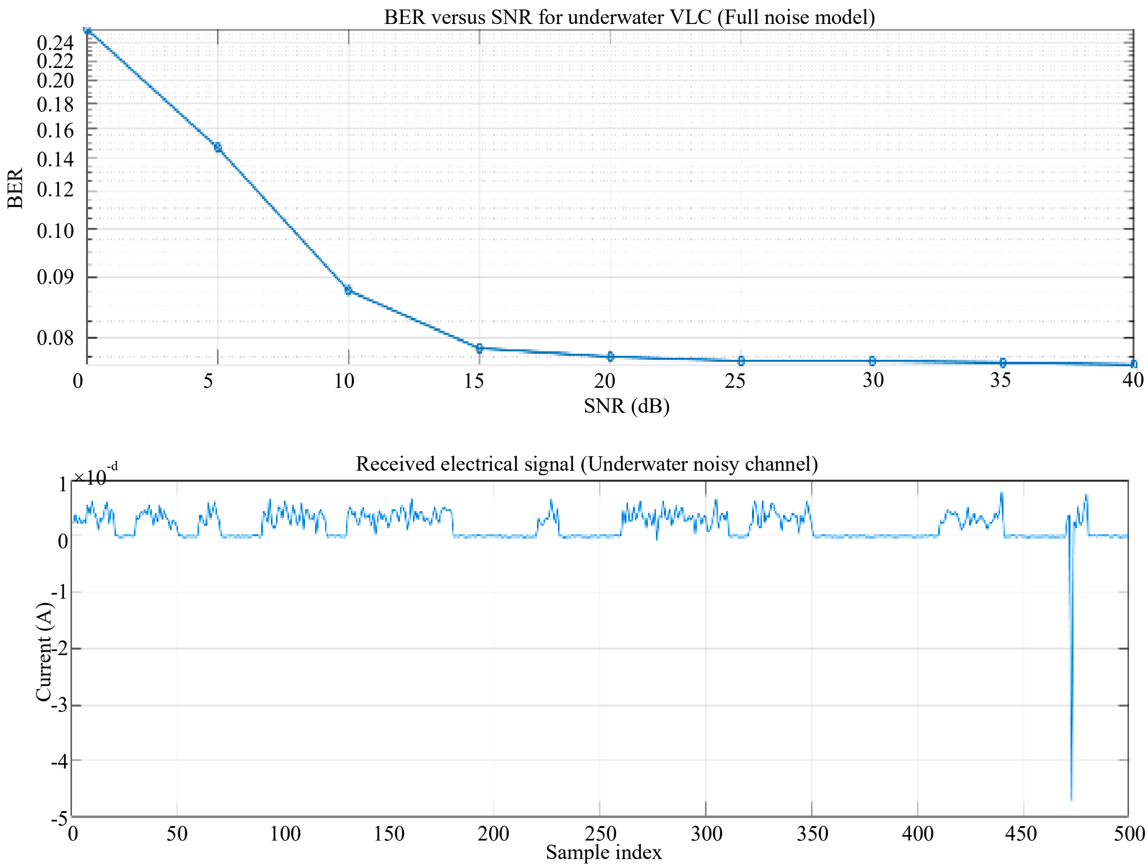

Figure 2. BER versus SNR (photodiode).

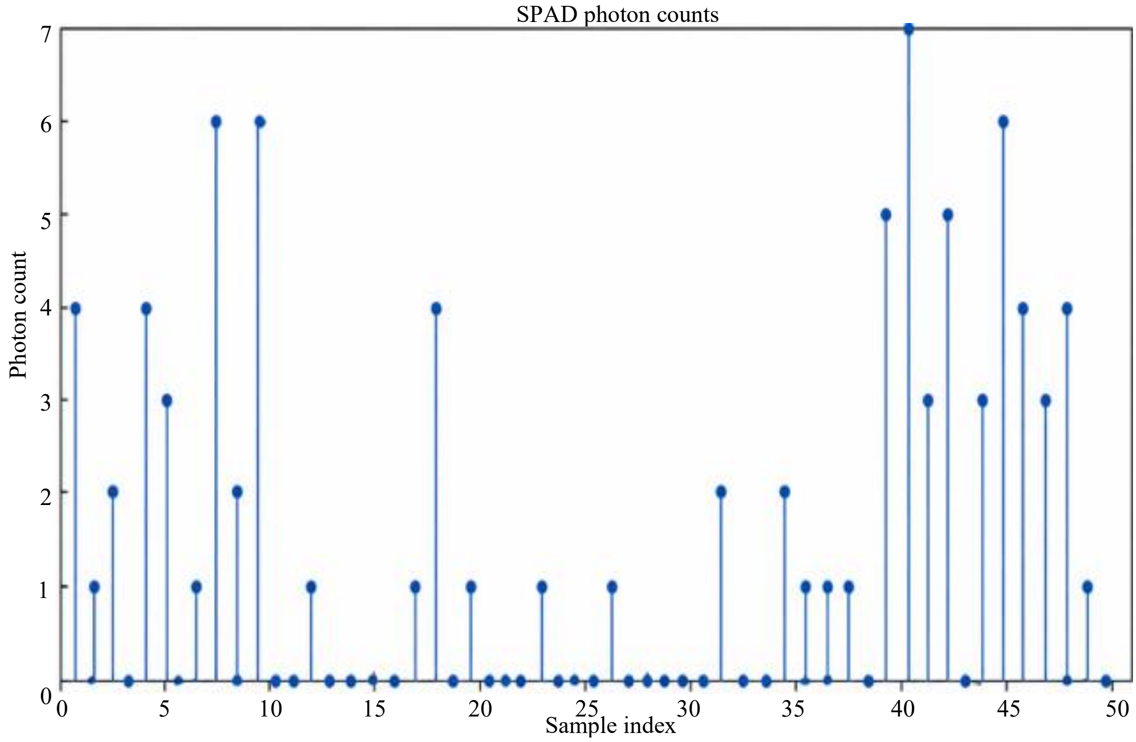

Figure 3. Photon count (SPAD receiver).

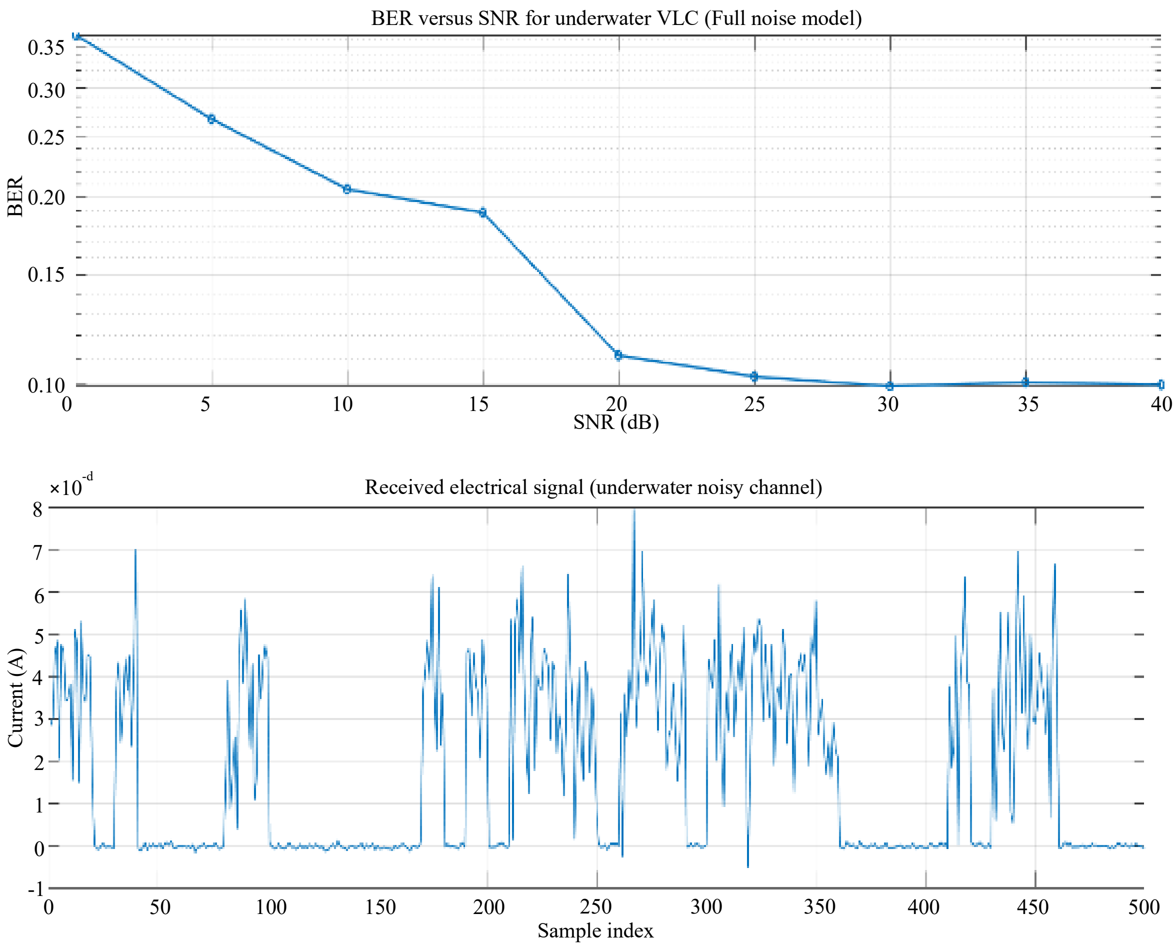

Figure 4. BER versus SNR (SPAD receiver).

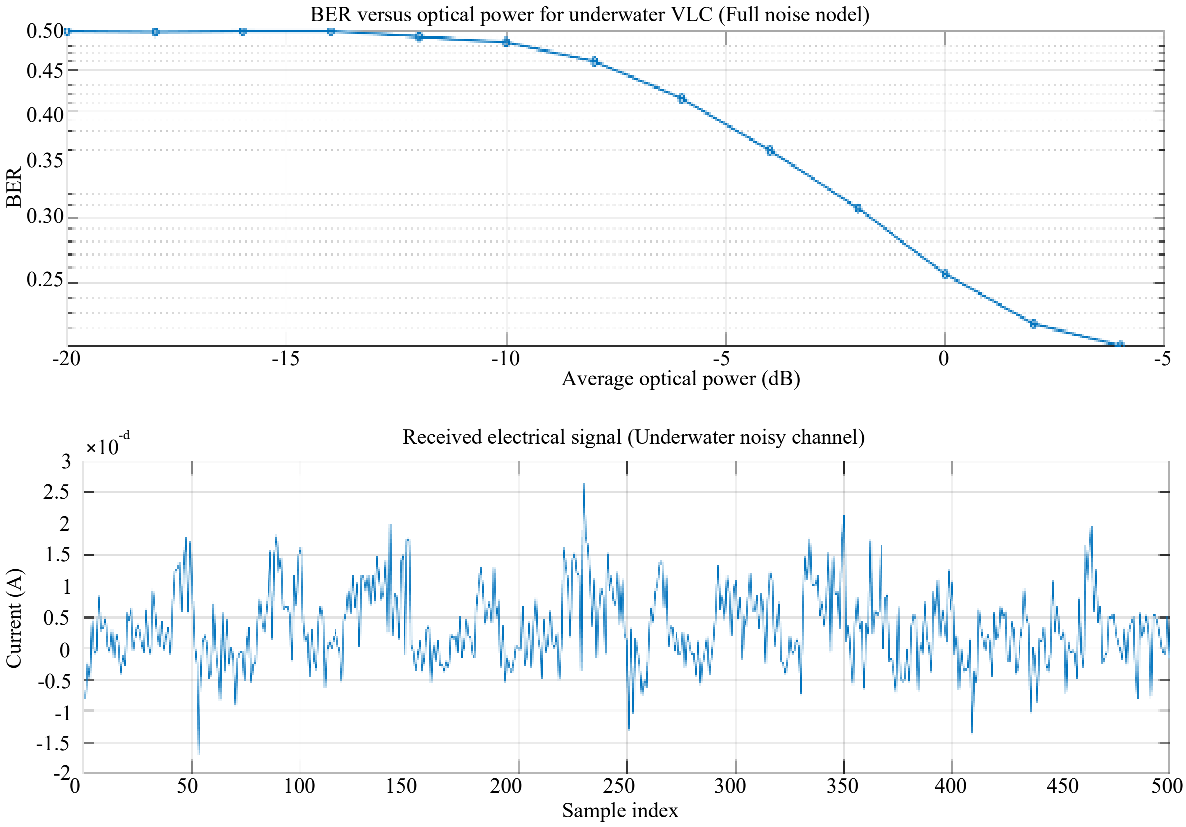

Figure 5. BER versus optical power.

This result clearly indicates that the proposed SPAD-based system outperforms conventional photodiode receivers, particularly under low-signal conditions. The improvement in the BER demonstrates the effectiveness of photon-counting detection in underwater VLC systems.

The upper plot in Figure 5 shows the variation of the BER with respect to the average optical power in the underwater VLC system. As optical power increased, the BER decreased, indicating improved signal detection and communication reliability. Higher optical power results in stronger received signals and fewer transmission errors. The lower plot illustrates the received electrical signal affected by the underwater channel noise. The fluctuations in the signal represent the effects of attenuation and noise during optical signal propagation.

This result clearly indicates that the proposed SPAD-based system outperforms conventional photodiode receivers, particularly under low-signal conditions. The improvement in the BER demonstrates the effectiveness of photon-counting detection in underwater VLC systems.

This section evaluates the performance of GLBD under different turbulence conditions:

$\alpha = 0.1$ (weak turbulence), as shown in Figure 6.

The BER is low, and the system performs efficiently with minimal signal fluctuations.

$\alpha = 0.3$ (moderate turbulence), as shown in Figure 7.

BER slightly increases due to channel variations, but GLBD maintains stable performance.

$\alpha = 0.6$ (strong turbulence), as shown in Figure 8.

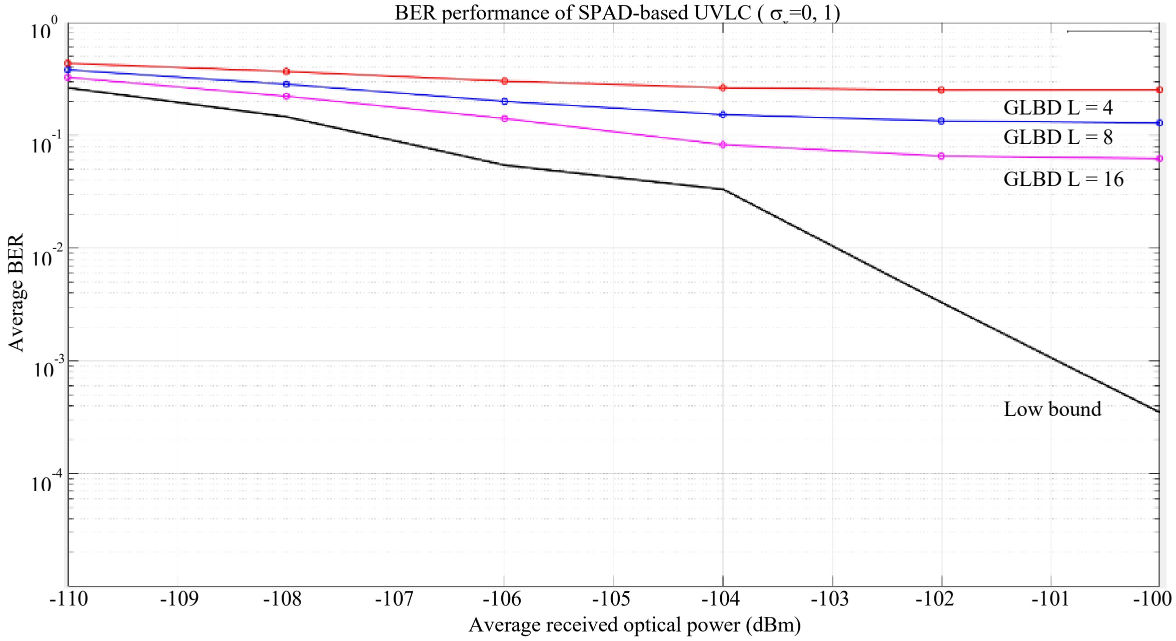

Figure 6. GLBD under turbulence conditions (α = 0.1).

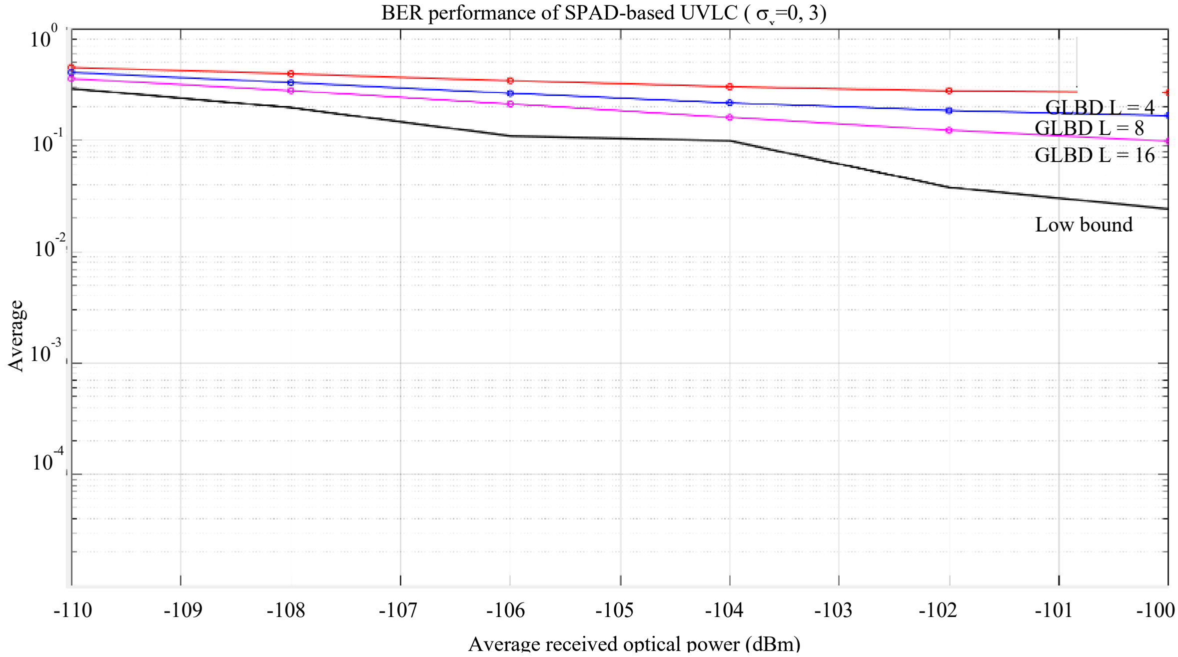

Figure 7. GLBD under turbulence conditions (α = 0.3).

The BER increases significantly owing to severe signal fading; however, the GLBD still performs better than the conventional methods.

This shows that GLBD is robust under varying underwater channel conditions. $a = 0.1$

GLBD Versus MSD

This section compares the performances of the GLBD and MSD detection techniques, as shown in Figure 9. GLBD achieves a lower BER than MSD, particularly under turbulent conditions, because it performs block-based likelihood detection without requiring prior channel knowledge. MSD improves accuracy compared to basic methods but has a higher computational complexity.

GLBD with Block Coding

This analysis shows the performance improvement when block coding is applied with GLBD, as shown in Figure 10. Block coding helps eliminate the error floor by avoiding long sequences with identical bits. Consequently, the BER is significantly reduced, and the detection reliability is improved compared to that of the uncoded GLBD.

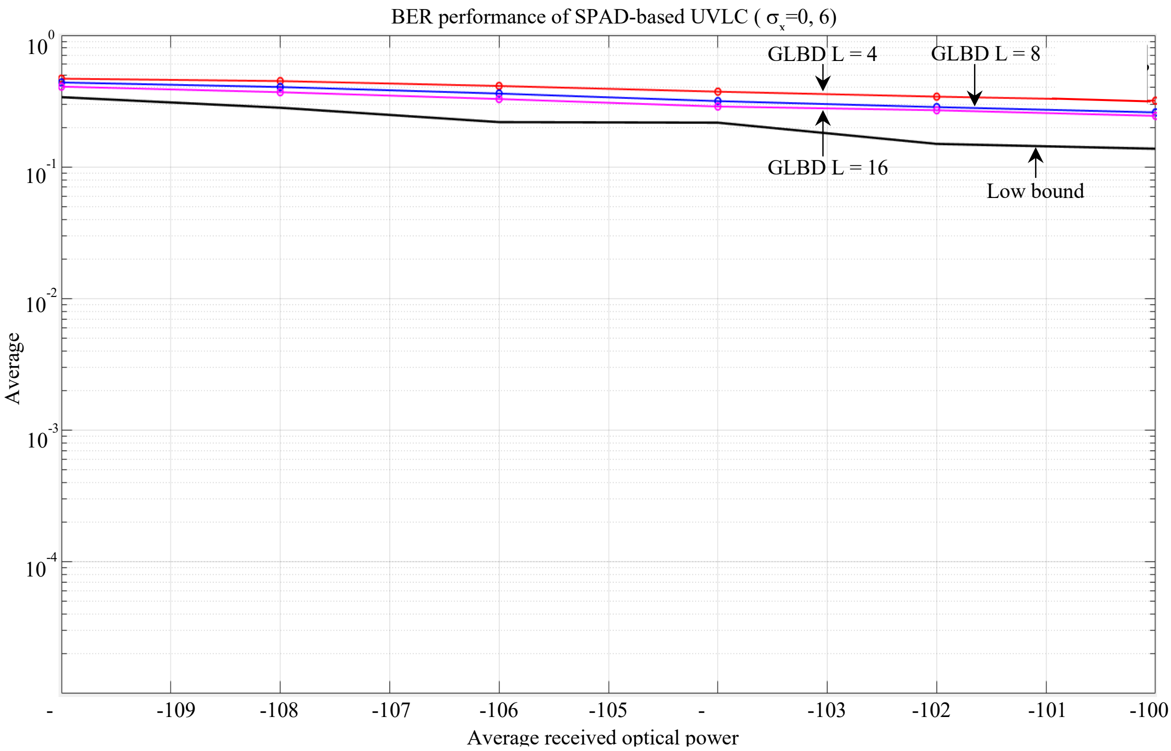

Figure 8. GLBD under turbulence conditions (α = 0.6).

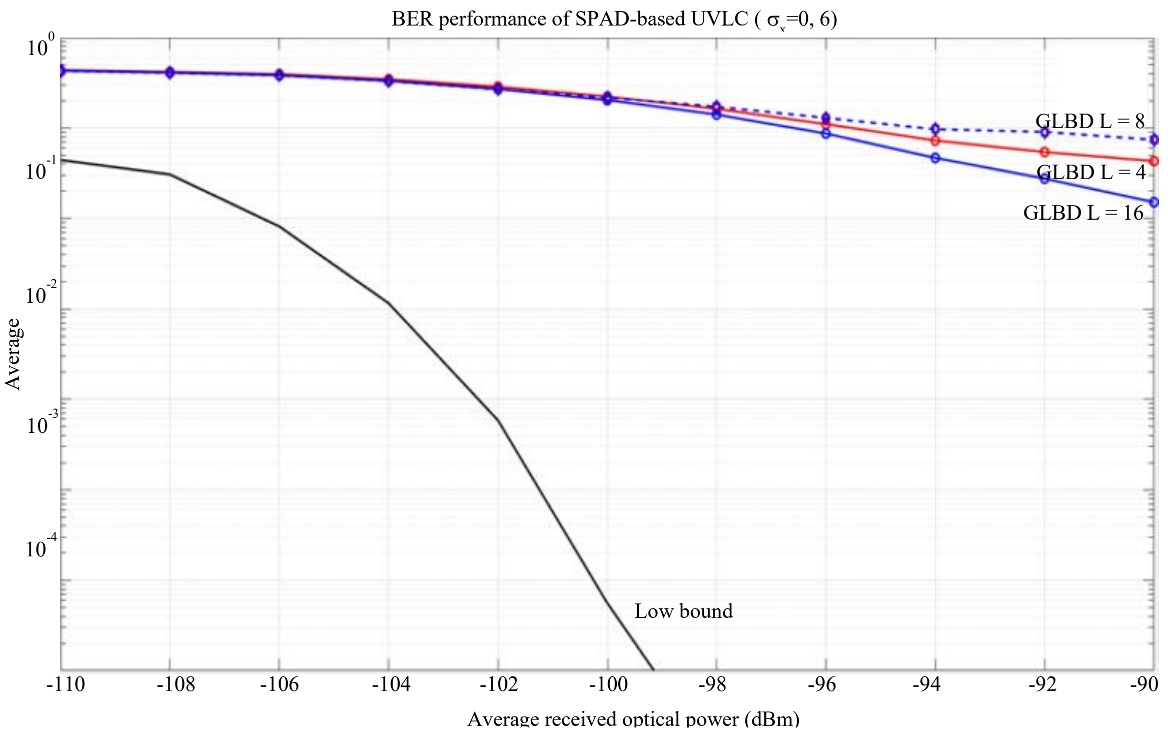

Figure 9. GLBD versus MSD (α = 0.1).

GLBD with Fast Search

This section evaluates the performance of the GLBD with a fast search algorithm, as shown in Figure 11. The algorithm reduces the computational complexity by limiting the number of possible sequences evaluated during detection. Despite this reduction, the BER performance remains almost unchanged, indicating that efficiency is improved without affecting the accuracy

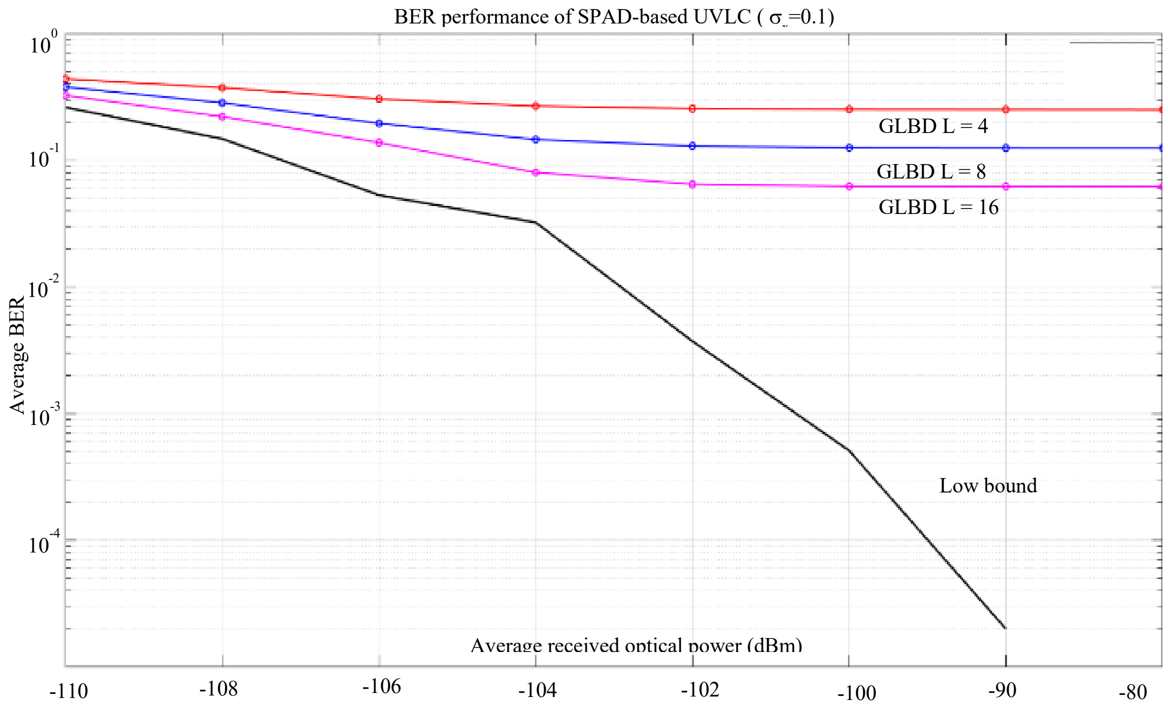

Figure 10. GLBD with block coding.

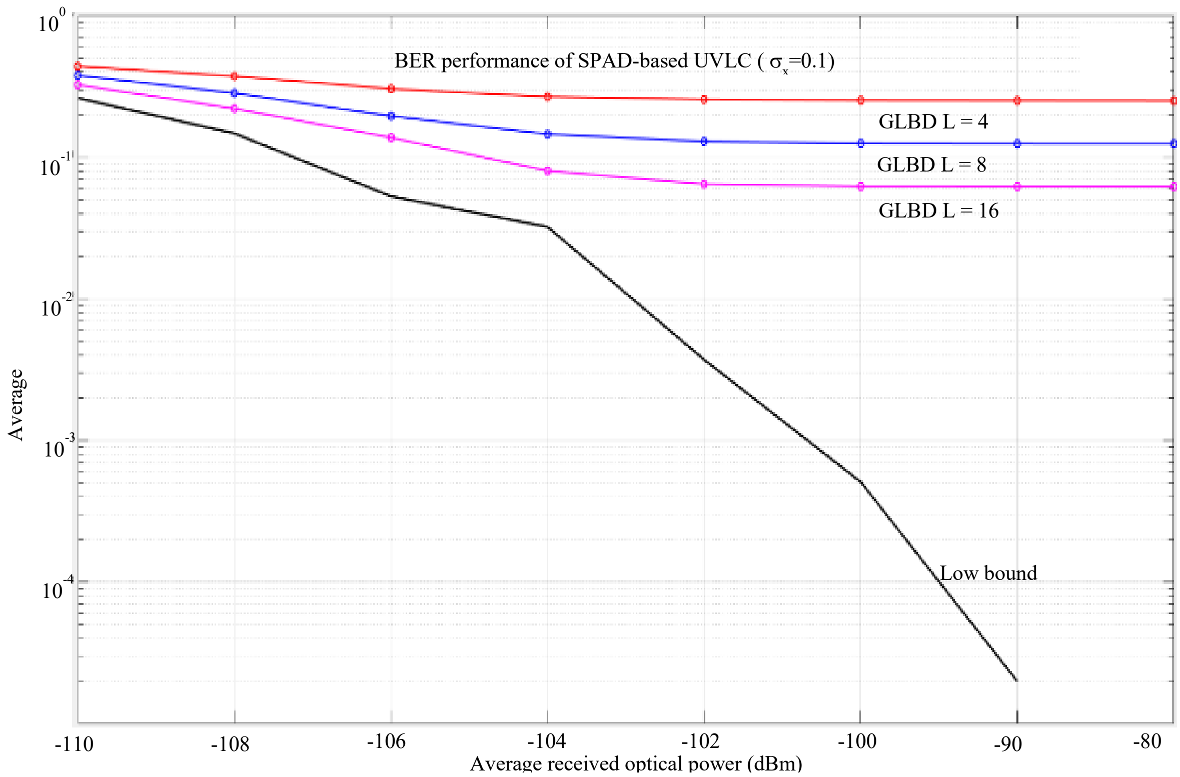

Figure 11. GLBD with fast search algorithm.

In addition to the BER versus SNR and BER versus optical power analyses, the system performance was further evaluated under different turbulence conditions ($\alpha = 0.1$, 0.3, and 0.6). It is observed that as turbulence increases, the BER also increases owing to signal fluctuations. However, GLBD maintained a stable performance compared to conventional methods.

A comparison between GLBD and MSD shows that GLBD achieves a lower BER, particularly under high-turbulence conditions. MSD improves performance compared to threshold detection but suffers from higher computational complexity.

Furthermore, the implementation of block coding significantly reduces the BER by eliminating the error floor, whereas the fast search algorithm reduces the computational complexity without affecting the detection performance. These results demonstrate that the proposed system is efficient and robust in practical underwater conditions.

CONCLUSION

This paper presents an enhanced underwater VLC system as an efficient alternative to conventional acoustic and RF communication methods. The system utilizes LED-based optical transmission with on–off keying (OOK) modulation to enable high-speed short-range underwater communication. The impact of underwater channel impairments, such as absorption, scattering, and turbulence, is considered to model realistic propagation conditions. A SPAD receiver was employed for photon-counting detection, providing high sensitivity under low optical power conditions. Advanced detection techniques, such as GLBD and MSD, are implemented to improve the signal detection performance. Among these, the GLBD achieves a superior BER performance and demonstrates robustness under turbulent conditions, whereas the MSD enhances detection accuracy at the cost of increased computational complexity.

Furthermore, block coding is applied to reduce the error rates, and a fast search algorithm is used to improve computational efficiency. The results confirm that the proposed system achieves reliable communication with improved BER performance. The system can be effectively applied in real-world scenarios, such as underwater surveillance, marine data collection, and communication between autonomous underwater vehicles (AUVs), making it a promising solution for next-generation underwater communication technologies.

Future Scope

Future work can focus on improving the underwater VLC performance under varying channel conditions, such as turbulence and noise. Advanced detection and coding techniques may further enhance BER performance and communication reliability. Extending the system to MIMO-based VLC architectures and validating its performance through real underwater experiments can support the practical deployment of underwater optical wireless communication systems.

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