Optimization of Link Distance and Receiver Parameters for Efficient Underwater Communication Using Monte-Carlo Simulation

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Abstract

This study examines the propagation characteristics of laser beams in underwater wireless optical communication channels through Monte Carlo simulations across various ocean water types. A line-of-sight system utilizing a laser diode with a 532 nm wavelength and a beam divergence of 12 mrad demonstrates enhanced propagation performance compared to an LED in all tested water conditions. Notably, propagation distances surpassing 150 meters in pure sea water and 68 meters in clear ocean water are observed.

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Introduction

The ocean is a vast and mysterious place. It has many secrets that are yet to be uncovered. This has led to growing interest in underwater exploration. Many fields are interested in this, including science, environment, commerce, and defense [1]. Underwater wireless communication is essential for many applications including submarine communication, monitoring seismic activity, tracking pollution, disaster management, fisheries and ecological research [2]. Radio waves have trouble traveling through water. Acoustic signals also have limitations, such as low bandwidth and slow transmission speeds [3].

Underwater wireless optical communication (UWOC) is a promising solution. It offers many advantages, including high data rates, cost efficiency, and precise directivity [4]. However, seawater has complex optical properties. These properties make it difficult for UWOC signals to travel far. One of the biggest challenges is attenuation. To overcome this challenge, UWOC systems use specific wavelengths. These wavelengths are in the blue-green spectrum (430–550 nm). They experience less attenuation in underwater environments [5].

This research advances UWOC technology by achieving transmission distances of 150 meters in pure sea water and 68 meters in clear ocean water. These distances represent improvements of 53% and 48%, respectively, at a 50 dB loss threshold [6]. We used Monte Carlo simulations to optimize UWOC system performance. Our simulations analyzed various factors, including source and receiver configurations, channel characteristics, and beam types [7].

Method

This study models an Underwater Wireless Optical Communication (UWOC) system utilizing Monte Carlo simulations to analyze photon propagation in oceanic water, considering the effects of absorption and scattering. Four types of water are considered in this simulation: Pure Sea, Clear Ocean, Coastal and Turbid harbor water. Absorption and scattering coefficients for different water types at a wavelength of 532 nm are incorporated into the model [8] (Table 1).

Table 1: Characteristics of propagation channel.

Water type	Absorption coefficient (m^{-1})	Scattering coefficient (m^{-1})
Pure sea Water	0.053	0.003
Clear Ocean Water	0.069	0.080
Coastal Water	0.088	0.216
Turbid Harbor Water	0.295	1.875

A 532 nm laser diode serves as the light source, enabling realistic simulations. Other Simulation parameters are set as following: the beam width = 2mm and the field of view of the receiver (FOV) were chosen to be 180 degrees to maximize the collection of the scattered photons. The beam divergence was -12mrad to +12mrad. The distance between the source and the receiver was varied between 5 to 160 m to investigate the intensity loss profile. Minimum 10^6 photons were used per simulation.

The schematic diagram of the line-of-sight (LOS) UWOC system analyzed in this study is illustrated in figure 1.

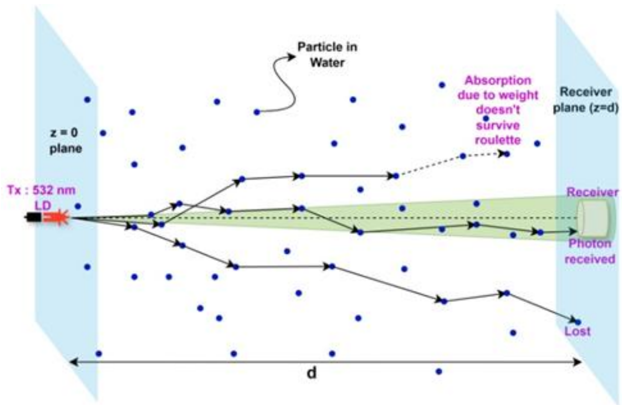

Figure 1: Schematic diagram of a line-of-sight underwater wireless optical communication channel showing absorbed received and lost photons.

Monte Carlo Simulation

The algorithm that is used to perform the Monte Carlo Simulation is summarized in the flowchart in figure 2.

The Monte Carlo simulation launches photons with an initial unity weight, allowing them to interact with the water medium, where they lose weight and alter direction due to scattering. Random sampling techniques are employed to determine step sizes, scattering angles, and the launch direction. This simulates the random behaviour of photon propagation, allowing for the modelling of complex scenarios. By introducing randomness, the simulation can capture the stochastic nature of photon interactions, providing a more realistic representation of photon trajectory and behaviour. This enables accurate modelling of underwater wireless optical communication systems. The photon's trajectory is continuously updated until termination using the roulette method. The simulation ensures high-fidelity photon detection at the receiver, accurately recording their intensity and arrival times. This detailed modelling framework facilitates the performance analysis and optimization of the UWOC system.

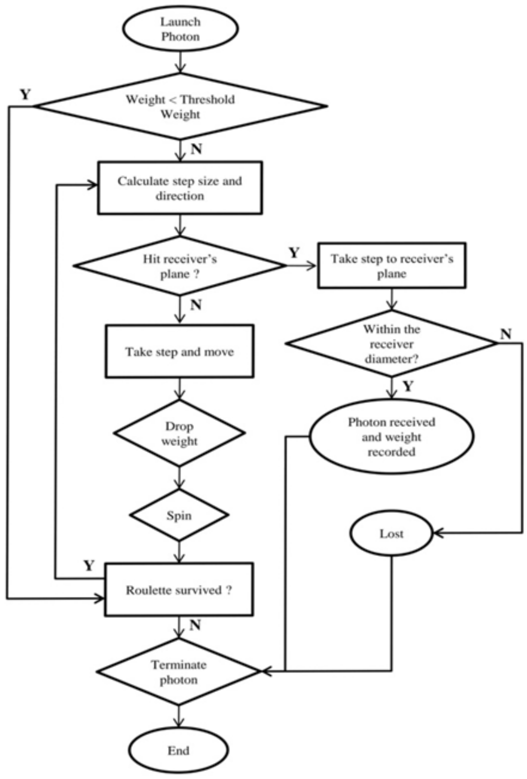

Figure 2: Flow Chart of Monte Carlo Simulation.

Discussion

In a line-of-sight configuration, a 532 nm laser diode with a 12 mrad beam divergence demonstrated propagation distances exceeding 150 meters in pure sea water and 68 meters in clear ocean water. In pure sea water, the laser beam maintained a minimal loss of approximately -45 dB over a 150-meter range.

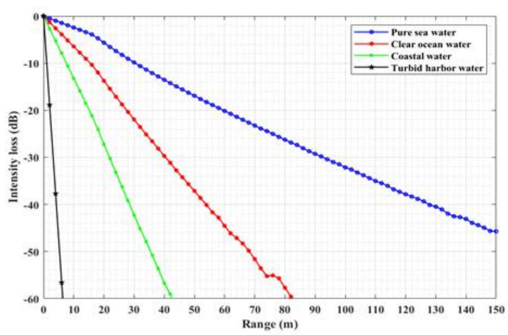

Figure 3: Received Intensity as a function of distance for different water types.

These results confirm that the laser diode outperforms an

LED across all water types, highlighting its superior capability for underwater communication. Additionally, it was observed that increasing the receiver diameter significantly reduces intensity loss, further improving system performance.

The comparison of intensity loss values for various water types with previous studies, as well as the effect of varying receiver diameter is reported in table 2.

Table 2: Comparison with Previous Work.

Water type	Link Distance	Receiver lens Diameter (cm.)	Intensity loss (dB) when source is LED	Intensity loss (dB) Reported in this paper
Pure sea	20	20	-23.50	-5.65
Clear Ocean	20	20	-30.41	-13.73
Coastal	20	20	-39.74	-27.19
Clear Ocean	20	0.5	-48.38	-32.19
Clear Ocean	20	2	-41.44	-24.13
Clear Ocean	20	50	-25.89	-12.93
Clear Ocean	10	20	-21.23	-6.45
Clear Ocean	50	20	-53.52	-37.17

Conclusion and Future Prospective

Successful transmissions were achieved over distances of 150 meters in pure seawater, surpassing existing limits by 53%. Similarly, successful transmissions of 68 meters in clear ocean water and 36 meters in coastal water were accomplished, exceeding current limits by 48% and 33%, respectively, with a 50 dB signal loss. These results confirm that a line-of-sight configuration using a laser diode outperforms LEDs across all water types. Additionally, optimizing the receiver diameter and the initial beam divergence angle significantly enhances underwater communication performance. Notably, increasing the receiver diameter helps reduce intensity loss, making it suitable for applications in off-line-of-sight communication. By understanding how these factors influence intensity loss, we can design more efficient underwater wireless optical communication systems using various beam configurations.

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