Spectrally resolved characterization of thermally induced underwater turbulence using a broadband white-light interrogator

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Abstract: To allow for reliable wireless optical links in realistic underwater environments, we study the dependence of turbulence-induced fading on the wavelength using a laser-based white-light interrogator in emulated realistic conditions. We experimentally show that the scintillation index decreases significantly with the increase of wavelength. The results are verified for longer distances using a Monte Carlo simulation. We numerically and experimentally demonstrate that the use of longer wavelengths lowers the bit error ratio by as much as three orders of magnitude. We conclude that using green light is more reliable in turbulent channels than blue. The correlation between different wavelengths under turbulence is studied, which was made possible by the use of the laser-based white-light interrogator.

Index Terms: Underwater wireless optical communication (UWOC), oceanic turbulence.

1. Introduction

With recent advancement in the field of underwater communication, and with the futuristic vision of internet of underwater things (IoUT) [1], underwater wireless optical communication (UWOC) has garnered significant attention in recent years [2]–[5] owing to their high modulation speeds compared to other technologies. Currently, acoustic technologies dominate the field of wireless communication underwater [6]–[8], since the use of radio frequency in water faces major challenges that include the size and complexity of the antennas and the high attenuation it encounters in seawater [9]. However, the use of acoustic communication suffers from high latency and low data rates [10], which limits their applications. On the other hand, while UWOC technology allows for high-speed communication, it also must overcome serious challenges. One of these hurdles is the strict requirement on the alignment between the transmitter and the receiver, given how small traditional optical receivers are. This alignment becomes more challenging in real environments that suffer from turbulence, which is the random variations in the refraction index of the water, since these variations change the path of the light beam. Researchers have dedicated considerable
efforts in order to characterize the underwater channel in the presence of turbulence that is caused by different factors, including temperature variations, salinity variations, and bubbles populations [11]–[14].

Since emulating UWOC links in laboratory testbeds is not always practical, especially if long-distance tests are required, computer simulations have been utilized by researchers to conveniently approximate realistic conditions. One of the methods used for this purpose is Monte Carlo simulations. Different approaches are used to simulate the effects of absorption and scattering, and with these approaches, researchers were able to simulate different configurations of UWOC links [15], [16], including line-of-sight (LOS) [17] and non-line-of-sight (NLOS) [18], [19] links. Moreover, a Monte Carlo simulation was used in [20] to study underwater turbulence based on the refraction index model presented in [21].

With better knowledge of the performance of UWOC links in different turbulence scenarios, it is possible to mitigate its effects. In [22], Oubei et al. demonstrated that the use of wider beams can improve the performance in the presence of bubbles in the water while in [23], it was shown that the scintillation index of a red laser is smaller than that of green and blue lasers. In [11], [24], spatial diversity techniques were implemented in multiple-input multiple-output (MIMO) systems in order to alleviate the degradation caused by turbulence. However, the use of spatial diversity means an increase in the difficulty of the alignment, since the number of transmitters and receivers is increased. On the other hand, wavelength diversity does not suffer from this issue because it is possible to use multiple superimposed beams with different wavelengths such that the complexity of the alignment is not increased, since the beams can be decomposed after reception.

In this work, we experimentally study the wavelength dependence of turbulence-induced fading by implementing a comprehensive technique that utilizes a laser-based white-light interrogator to study the effects of turbulence on different wavelengths traveling through the channel simultaneously. A Monte Carlo simulation is also used to verify the experimental results. We then compare the effect of turbulence on the bit error ratio (BER) using on-off keying (OOK) for different wavelengths. Finally, we investigate the correlation between different wavelengths, since studying the correlation between the channels in a MIMO link is critical in achieving the highest diversity gain. The use of laser-based white light provides rich information about the channel such that the optimal power allocation among the deployed red-green-blue-wavelength laser transmitters can be implemented.

2. Experimental Details

To study the effect of turbulence on different wavelengths, we used a laser-based white light source (SaNoor SNWL-3A), whose spectrum is shown in Fig. 1(a), as the transmitter. Figure 1(b) shows an image of the laser used. The white light is achieved by using a blue laser followed by yellow ceramic phosphor. The wide range of wavelengths provided by this laser allows for transmitting different wavelengths through the same medium such that they experience the same conditions, especially those caused by turbulence. The peak, which occurs at 457 nm, is neglected since its intensity exceeds the range of the used detector, causing it to be saturated and preventing it from recording the variations in the intensity at that particular wavelength. In Fig. 1(a), the integration time of the spectrometer was set at 10 ms to avoid the saturation at the peak. However, during the experiment, the integration time was 50 ms, which increases the intensity of the recorded spectra. This helps in including more wavelengths in the study. The wavelength range of interest in this experiment is that from 480 nm to 680 nm. A power supply (Keithley 2400 SourceMeter) is used to supply an injection current of 850 mA, generating an optical power of 216.7 mW, which was measured using a power meter (Newport 2936-C) with the wavelength set at 457 nm and a silicon photodetector (Newport 818-SL/DB). The laser is followed by an anti-reflective-coated 2-inch aspheric lens (Thorlabs ACL50832U-A) for collimation, and the output beam from the lens had a diameter of 4 cm. The channel was a water tank with a water chiller on each of its ends. The chillers are connected to the tank through water tubes that are used for suction in the middle
and for pumping water on the sides (cold water on one end and warm water on the other). The tank is 1.0-m long and has a square cross section whose sides are 0.12-m long. Light passes through 0.06 m × 0.06 m optical windows on both ends.

On the receiving end, a 3-inch aspheric lens with an anti-reflective coating (Thorlabs ACL7560U-A) is used to focus the light into an optical fiber. Two reflective neutral density (ND) filters, Thorlabs ND05A (ND=0.5) and ND20A (ND=2.0), decrease the incident optical power going into the fiber to avoid saturation. The spectrometer (Ocean Optics HR4000 with a 5-µm slit) is connected to a computer that is used to control it and to record data. Figure 2 shows the experimental setup. The water in the tank is obtained from a water purification system (Millipore Milli-Q Academic) and a 40-ppt salt concentration is then added to emulate the environment of the Red Sea [25]. Five different temperature gradients are created using the two chillers. The temperature of the water on the transmitter’s side is varied from 20 °C to 24 °C while the water temperature on the receiver’s end is varied from 30 °C to 26 °C, in steps of 1 °C, creating the following temperature gradients: 0.10, 0.08, 0.06, 0.04, and 0.02 °C/cm. In all these cases, the average temperature is 25 °C and the continuous flow of the water through the tank maintains the temperature gradient.

3. Results

3.1. Scintillation Index (Experimental Results)

The spectrometer was set to record 1,000 spectra in each channel scenario. By monitoring the variations in the spectrum from one sample to the others, we are able to calculate the scintillation index, $\sigma^2_I(\lambda)$, using:

$$\sigma^2_I(\lambda) = \frac{\langle I(\lambda)^2 \rangle - \langle I(\lambda) \rangle^2}{\langle I(\lambda) \rangle^2},$$

Fig. 2: Experimental setup with temperature gradients that increase away from the transmitter.
where $I(\lambda)$ is the received intensity for wavelength $\lambda$ and the angle brackets denote the time-average operator. Each recorded spectrum is considered a sample of $I(\lambda)$. Figure 3(a) shows the scintillation index as a function of the wavelength in the range from 480 nm to 680 nm in the presence of each of the five different temperature gradients, while Fig. 3(b) shows samples of the spectrum at different instants under a $0.10-°C/cm$ temperature gradient. Since the scintillation index relies on the normalized intensity, rather than the absolute intensity, the difference in the intensities of the different wavelengths has no effect on the calculations.

As can be clearly observed from Fig. 3(a), the increase of the wavelength decreases the scintillation index, which means that longer wavelengths suffer less from the effects of the introduced turbulence. This is in line with numerical results [26] and theoretical expectations. To show this, we can consider the Rytov variance, $\sigma_R^2$, which can be expressed as [27]:

$$\sigma_R^2 = 1.23 C_n^2 \left( \frac{2\pi}{\lambda} \right)^{7/6} L^{11/6},$$

where $C_n^2$ is the refractive index structure parameter and $L$ is the length of the channel. Under weak irradiance fluctuations, which is characterized by $\sigma_I^2$ values less than unity, the scintillation index changes linearly with the Rytov variance [27]. Since the Rytov variance is inversely proportional to the wavelength, the scintillation index must be lower for longer wavelengths.

When comparing the scintillation index of long wavelengths to that of shorter wavelengths, a total drop between 70 and 83% is observed in all scenarios. This significant difference shows that in some cases, the use of longer wavelengths, in data transmission underwater might be more practical than shorter wavelengths when underwater turbulence is severe. This is especially true for cases in which the transmitter has enough power to transmit long-wavelength light for relatively long distances, which corresponds to channels that are less homogeneous. For example, a green laser beam, which is commonly used in UWOC, would be more immune to turbulence-induced fading when compared to a blue laser beam, especially that the scintillation index values drop rapidly as the wavelength increases.

3.2. Scintillation Index (Simulation Results)

To extend the discussion to consider small temperature gradients along long distances, we used the Monte Carlo simulation algorithm presented in [20] with a few modifications, including corrections to Equations 15-17 to include the refraction indices of adjacent layers. We simulated two temperature gradients, 0.010 and 0.005 $°C/cm$, along a transmission distance of 10 m. For
Fig. 4: Scintillation index as a function of wavelength obtained from the Monte Carlo simulation. Longer wavelengths are less sensitive to turbulence, showing that the use of green light is more reliable than blue in turbulent UWOC channels.

The first scenario, the water temperature on the transmitter’s side was set to 20 °C while on the receiver’s end, it was set to 30 °C. For the second scenario, the temperatures were 22.5 and 27.5 °C at the transmitter’s and the receiver’s sides, respectively. The salt concentration in each layer was randomly picked from a uniform distribution from 39.7 to 40.3 ppt. Since the experiment was conducted in a shallow water tank, we neglected the effects of the pressure. We considered five wavelengths: 500, 550, 600, 650, and 700 nm. We restricted the study to the wavelength range from 500 to 700 nm because the refraction index model described in [21] produces reliably accurate results in this range.

The intensity in each sample was obtained by launching 10,000 photons of each wavelength. The conditions faced by the photons are identical for all wavelengths. After recording the intensity for 1,000 samples, the scintillation index is calculated for each wavelength. Figure 4 shows the scintillation index obtained from the Monte Carlo simulation as a function of the wavelength. These results follow a similar trend when compared to the experimental results in Fig. 3(a), with shorter wavelengths being more severely degraded by the simulated turbulence in both scenarios. We can expect that wavelengths shorter than 500 nm, which were not included due to the limitations of the model, will have even higher scintillation index values, which shows the advantage of using 520-nm green light in turbulent channels over 480-nm blue light.

3.3. OOK Performance Evaluation

By using the spectra recorded from the spectrometer and the laser-based white light, we can numerically estimate the BER for all the studied wavelengths. Assuming an OOK UWOC link, we can calculate the average BER using [27], [28]:

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\text{BER} = \int_{0}^{\infty} \frac{1}{2} f_{I_{\lambda}}(i_{\lambda}) \text{erfc} \left( \frac{\sqrt{\text{SNR}_{I_{\lambda}}}}{2} \right) \, di_{\lambda},
\]

where \( f_{I_{\lambda}}(i_{\lambda}) \) is the probability density function (PDF) of the received intensity at wavelength \( \lambda \), \( \text{SNR} \) is the average signal-to-noise ratio (SNR), and \( \text{erfc}(\cdot) \) is the complementary error function. The PDF is approximated from the collected empirical data using a normal kernel function estimate. Figure 5 shows the average BER versus the average SNR for two different temperature gradients: 0.10 and 0.02 °C/cm and for six wavelengths. The average BER is observed to significantly decrease as the wavelength increases, especially for high average SNR values and for the larger temperature gradient.
To investigate the negative effects of the underwater turbulence on UWOC links, we experimentally measured the BER for three different lasers: a 450-nm blue laser (Thorlabs LP450-SF15), a 520-nm green laser (Thorlabs LP520-SF15), and a 642-nm red laser (Thorlabs LP642-SF20), under temperature-induced turbulence. The water used is the same as the one described in Section 2, but without adding salt. The white-light source is replaced by each of the three lasers and they are tested sequentially under the same conditions. The receiver is a high-speed Si avalanche photodetector (Menlo Systems APD 210). On the receiver’s end, a variable attenuator is used to avoid saturating the detector. Since the power used for all lasers was enough for the beams to travel through the 1-m channel, the effects observed can be attributed mostly to turbulence. A BER tester (Agilent N4903B J-BERT) is connected to the transmitter to send an OOK 1-Gbps pseudorandom binary sequence, and to the receiver for BER measurement. The BER values, accumulated for over one minute, for each of the three wavelengths under different conditions are shown in Fig. 6, in which the previously demonstrated green laser results are included for comparison purposes [23].

While the small temperature gradients did not considerably affect the BER, the degradation in the performance due to turbulence is significant in larger temperature gradients. However, the use of a longer wavelength enhanced the performance of the communication link. For example, under a 0.07 °C/cm temperature gradient, the BER for the blue laser is three orders of magnitude higher than that of the red laser and an order of magnitude higher than that of the green one. Moreover, the increase in the temperature gradient increased the BER values, especially for the blue and green lasers. Throughout the tested temperature-induced turbulence scenarios, data transmitted using longer wavelengths exhibited lower BER values.

We can conclude that using a green laser in a water channel that suffers from turbulence has the advantage of being less sensitive to turbulence-induced fading when compared to the use of a blue laser as well as having significantly lower attenuation in the water than a red laser beam. These results highlight an important tradeoff between choosing a short-wavelength laser (e.g., blue) to have lower attenuation and choosing a laser with a longer wavelength (e.g., green) that is less sensitive to the present turbulence. However, it is worth mentioning that red light was shown to have lower attenuation than blue and green light in highly turbid harbor water [29]. Selecting the best wavelength for such a single-input single-output (SISO) link depends on a variety of considerations, such as the length of the channel, its intrinsic optical properties, and the causes...
of turbulence, including temperature and salinity gradients. Another important factor is the size of the active area of the receiver, since having a smaller area would make the receiver more sensitive to scintillations.

**3.4. Correlation between Different Wavelengths**

In order to ensure better data reception in a UWOC link, it is possible to use wavelength diversity. One advantage of using wavelength diversity over using spatial diversity is that it does not increase the difficulty of alignment, which is a challenging task. This is because the different beams can be superimposed using optics such that the receiver will have to be aligned with a single beam only, which can be decomposed using optical filters if the wavelengths used are different. In this case, any relative rotation along the axis of the beam between the receiver and the transmitter would not result in misalignment. However, to make full use of such a MIMO system, the correlation between the different transmitted wavelengths must be studied, which is made possible because of the use of laser-based white light in interrogating the channel characteristics. By simultaneously recording the intensity values for all wavelengths in the white light, we calculate the correlation coefficient of each pair of wavelengths. The correlation matrices of wavelengths from 480 to 680 nm are shown in Fig. 7 for five temperature gradients. From the correlation matrices, we see that the correlation coefficient between wavelengths close to each other is higher than that between wavelengths that are further apart. This is true for all the tested turbulence scenarios. This high correlation means that, in the case of a wavelength-diversity MIMO system, the use of wavelengths that are close to each other might not provide the best performance.

For instance, if a MIMO system is utilizing a blue laser in the presence of turbulence, the use of a red laser as the second transmitter will result in lower correlation than the use of a green laser. This is desirable in MIMO configurations to increase the diversity gain, but the red laser will face higher attenuation, making it impractical for long-distance transmission, while the green laser will suffer from more scintillations and higher correlation with the blue laser. In addition to the aforementioned factors for the design of a SISO UWOC system, designing a MIMO system must take into consideration the high correlation between links utilizing wavelengths that are close to each other. The use of laser-based white light provides comprehensive channel characterization, allowing the transmitter to use the most suitable power allocation among the available wavelengths.

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**Fig. 6:** BER values for the green [23], blue, and red lasers under different temperature gradients. The blue-laser link suffers from higher BER values than the green-laser link, which strongly suggests the use of green lasers in turbulent UWOC channels.
4. Conclusions

We highlighted the advantages of using a laser-based white-light interrogator in channel characterization of UWOC links under the influence of turbulence. We experimentally demonstrated that the scintillation index of underwater links affected by temperature-induced turbulence decreases as the wavelength of the light increases. We carried out the experiment in different scenarios emulating the environment of the Red Sea. The results were verified using a Monte Carlo simulation in the case of longer transmission links with lower temperature gradients, which are challenging to emulate in laboratory testbeds. By studying OOK links, the degrading effects of turbulence on the BER were demonstrated. The numerical and experimental results showed that the use of a red laser decreased the average BER of a UWOC link under turbulence by as much as three orders of magnitude when compared to a blue laser. This significant difference highlights the importance of understanding the channel to be able to select the most suitable light source in a UWOC SISO link, but due to the high attenuation of red light in water, its use is not suitable for long-distance transmission. However, the use of a green laser as the transmitter gives the advantage of being capable of transmitting for longer distances when compared to a red laser due to the lower attenuation as well as having better immunity to turbulence-induced fading compared to a blue laser. The correlation matrix of underwater turbulence for different wavelengths, which was obtained using the laser-based white light, showed that the use of wavelengths that are further apart offers lower correlation, which is critical for wavelength-diversity MIMO links. The channel characterization enabled by the use of the laser-based white-light interrogator provides the needed information for the red-green-blue-wavelength laser transmitters to use the most suitable combination of wavelengths for reliable transmission.

References


