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Near-Infrared Wireless Optical Communication with Particulates In-Suspension over the Underwater Channel

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Abstract: We demonstrate a gigabit near-infrared-based underwater wireless optical communication link using an 808-nm laser diode to mitigate the particle scattering effect in turbid medium. An improvement in the error performance is observed with increasing concentrations.
OCIS codes: (010.4455) Oceanic propagation; (290.5850) Scattering, particles; (290.7050) Turbid media; (060.2605) Free-space optical communication

Over the past decade, a plethora of underwater communication technologies have emerged with the ultimate goal of realizing high-speed, large-bandwidth and long-distance marine communication. Underwater wireless optical communication (UWOC) has attracted considerable attention as a promising alternative over the conventional acoustic and radio frequency (RF) communication, due to its larger bandwidth, higher data rate, lower time latency, lower power consumption, and lower computational complexities [1].

The propagation of optical signal underwater is inevitably susceptible to the undesirable effects of water absorption and particle scattering [2], which are the dominant wavelength-dependent phenomenon resulting in the overall attenuation and change in direction of the optical beam, respectively [3]. Prior experimental demonstrations of the UWOC systems [4]–[6] have emphasized on the blue-to-green spectral regime under clear water condition, mainly due to the lower spectral beam attenuation between 450 nm and 550 nm as compared to the ultraviolet (UV) and near-infrared (NIR) regime. Microscopic organic and/or inorganic particulates suspended in different ocean and turbid coastal or harbor waters will alter the propagation characteristics of the optical beam underwater, thereby resulting in higher signal attenuation and affecting the overall performance of the UWOC system, particularly at higher particle concentrations [2]. While the blue-green visible spectra are commonly perceived as the most optimal choice of wavelengths for UWOC deployments, we report here on the experimental investigation of a UWOC link operating in the NIR regime by employing an 808 nm laser source, and demonstrate the feasibility of the NIR-based UWOC link in improving the error performance even at increasing water turbidities.

Figure 1 depicts the schematic of the experimental setup for a single-input single-output UWOC link employing the intensity modulation with direct detection (IM/DD) and the non-return-to-zero on-off-keying (NRZ-OOK) modulation. A high-power NIR laser diode (LD) with a peak emission wavelength of 0.8 μm at an optimal bias current of 383 mA is driven by the Thorlabs ITC4005 controller. An aspheric lens (Thorlabs A110TM-B) is used to collimate the optical beam. The pattern generator in the high-performance bit error rate (BER) tester (Agilent J-BERT N4903B) generates the pseudorandom binary sequence (PRBS) 2^{10} - 1 pattern at bit rate R_b, which is then modulated onto the instantaneous intensity of the optical beam wave. The information-bearing collimated beam propagates through a 1.5-meter-long water tank filled with fresh tap water to emulate the underwater channel.

The turbidity of the underwater conditions are produced with suspensions of $Al(OH)_3$ and $Mg(OH)_2$, which are found in a commercial antacid preparation (Maalox®). The Maalox solution is added to the water tank containing 25.2 liters of water to obtain concentrations of $N = \{3.0, 6.33, 9.67, 11.33\}$ g/m^3. Circulating pumps are evenly placed along the channel to maintain homogeneity of the diluted Maalox solution in the water tank. At the receiver, a plano-convex lens (Thorlabs LA1027-B) is used to focus the optical signals onto the avalanche photodetector (Menlo Systems APD210). The performance of the NIR-based UWOC link is analyzed using the J-BERT and digital communication analyzer (Agilent DCA 86100C) to measure the BER and eye diagram, respectively.

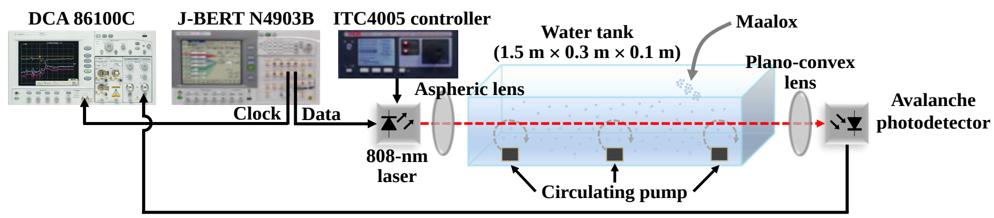

Fig. 1. Schematic of the experimental setup for the NIR-based UWOC link using an 808-nm LD.

Figure 2(a) illustrates the measured BER performance as a function of the received optical power under a more turbid underwater condition with a concentration of N = 3.0 g/m^3 (attenuation coefficient of 2.83 m^{-1}). At a higher bit rate of R_b = 1.5 Gbps, the UWOC link is subjected to a higher power requirement of -2 dBm to achieve the FEC limit criterion of 3.8 × 10^{-3}, as compared to R_b = 622 Mbps with a lower received power of -8 dBm. The power penalty is attributed to the bandwidth limitation of the system. In Fig. 2(b), we examine the effect of particle concentrations on the error performance at R_b = 1 Gbps. It is observed that the measured BER is improved with increasing amount of particulates suspended in the underwater channel albeit the reduction in received power due to the overall attenuation. The shifted trend of the BER towards the left (smaller received optical power) with higher concentrations can be explained by the fact that the NIR light with longer wavelength suffers from smaller scattering effect in turbid waters, and the forward scattering potentially directs the resultant beam towards the receiver [2], [7].

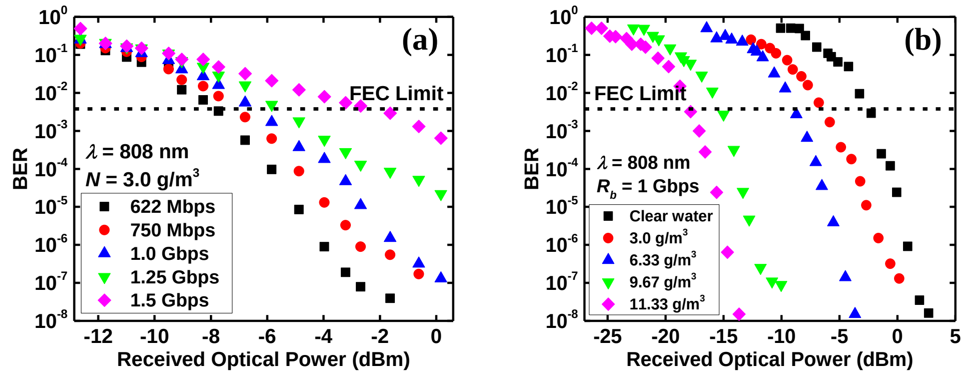

Fig. 2. Measured BER versus received optical power: (a) for N = 3.0 g/m^3 at R_b = {0.622, 0.75, 1.0, 1.25, 1.5} Gbps, and (b) for R_b = 1 Gbps at N = {0 (clear water), 3.0, 6.33, 9.67, 11.33} g/m^3.

Figure 3 shows the measured eye diagrams for R_b = 1 Gbps, with N = {0, 3.0, 6.33, 11.33} g/m^3. It is evident that a comparable wide opening of the eye is maintained for all the considered cases albeit the inherent signal attenuation from 2.77 dBm (clear water) to -13.66 dBm (11.33 g/m^3). These results reveal that the UWOC systems operating in the NIR regime are more resilient to the multiple scattering due to particulates in-suspension over the channel.

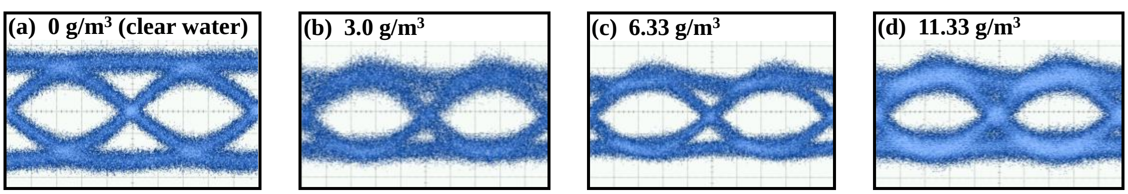

Fig. 3. Measured eye diagrams at R_b = 1 Gbps with increasing concentrations N: (a) 0 g/m^3 (clear water), (b) 3.0 g/m^3, (c) 6.33 g/m^3, and (d) 11.33 g/m^3. The received optical powers for the considered cases are {2.77, 0.16, -3.67, -13.66} dBm.

In summary, we have demonstrated a gigabit NIR-based underwater wireless transmission using an 808-nm LD, and evaluated the link error performance in turbid waters. It was shown that the measured BER is improved with increasing concentrations albeit the signal attenuation by more than 10 order-of-magnitude. The measured eye diagrams revealed that a comparable wide opening of the eye is maintained for all the considered cases. Therefore, UWOC links operating in the NIR regime with longer wavelengths are more resilient to the multiple scattering effects due to particulates in-suspension. With the availability of commercial high-power NIR lasers having high wall-plug efficiencies, we envision that the adoption of directly modulated NIR LDs would spur the realization of high-speed, large-bandwidth and long-distance UWOC systems that are robust to different water types.

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