Exploiting polarisation state for beyond 10 Gbps underwater optical wireless data transmission in hostile channel conditions

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ABSTRACT

This paper experimentally demonstrates the performance of subcarrier intensity modulation with polarisation division multiplexing (SIM-PDM) in a range of different water conditions. Underwater optical wireless communication (UOWC) is an emerging technology that offers high speed, low latency links over link distances in the order of metres. However, the effects of the UOWC channel present a challenge when designing a reliable link. These include: turbulence induced fading, which causes fluctuations in the received signal amplitude; particulate absorption, which causes an attenuation in the received optical power; and scattering, which causes spatial and temporal dispersion in the received signal. The SIM technique offers a resilience to turbulence compared to the state of the art on-off keying scheme, whilst additionally offering the potential for multi-level modulation orders – and therefore increased data rates – by encoding data on the signal phase as well as amplitude. In this work, PDM is used in conjunction with SIM to increase the spectral efficiency by separately modulating data across two orthogonal polarisation states. As long as these signals propagate identical channels, the polarisation states are maintained. Here, two orthogonally polarised laser beams are independently modulated with quadrature amplitude modulation (QAM), implemented via SIM to form the QAM-SIM-PDM technique. The performance of this technique is evaluated in terms of bit error rate and the maximum achievable data rate in clear, turbulent, and turbid water conditions. It is shown that data rates in excess of 10 Gbps are achievable using the QAM-SIM-PDM technique.

1. INTRODUCTION

Underwater optical wireless communications (UOWC) is an emerging technology with the potential to provide high speed links, over 10's of metres in the underwater environment. It is envisioned that this will enable further exploration of the oceans, environmental monitoring, and national security applications, among other applications. In these applications, it is expected that UOWC will act as a complementary technology to the dominant underwater acoustic communication (UAC) technology. In this future hybrid underwater network, UOWC is well suited to providing low latency, high speed communication links over short distances, whilst UAC will provide long range, low speed links. There are, however, challenges that must be overcome in order to develop a reliable UOWC system. One key challenge is to mitigate the effects of the UOWC channel on signal transmission.

As a photon propagates the UOWC channel it is subject to absorption and scattering from particles and water molecules.[1] The degree of absorption and scattering within a body of water is described as its turbidity. Absorption occurs when a photon interacts with matter and its energy is absorbed. The effect of absorption is observed as an attenuation in received signal. Whereas a scattering interaction occurs when the propagation direction of a photon is altered upon interaction with matter.[2] This causes both temporal and spatial spreading

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of the transmitted optical beam, yielding a reduction in the received signal and can cause an increase in inter-symbol interference (ISI) due to the multipath effect depending upon the link geometry. The turbidity of a channel can be quantified by the absorption, $a(\lambda)$, and scattering, $b(\lambda)$, coefficients that give the likelihood of either interaction occurring to a transmitted photon of wavelength λ. The combined likelihood of a photon interacting with matter whilst propagating the UOWC channel is the sum of these coefficients:[2]

$$c(\lambda) = a(\lambda) + b(\lambda). \tag{1}$$

These coefficients have been measured empirically in natural waters around the world. Reference[3] provides the channel coefficients derived from Jerlov's measurements, these provide a useful case study when investigating the performance of a UOWC system in the laboratory or through simulation.

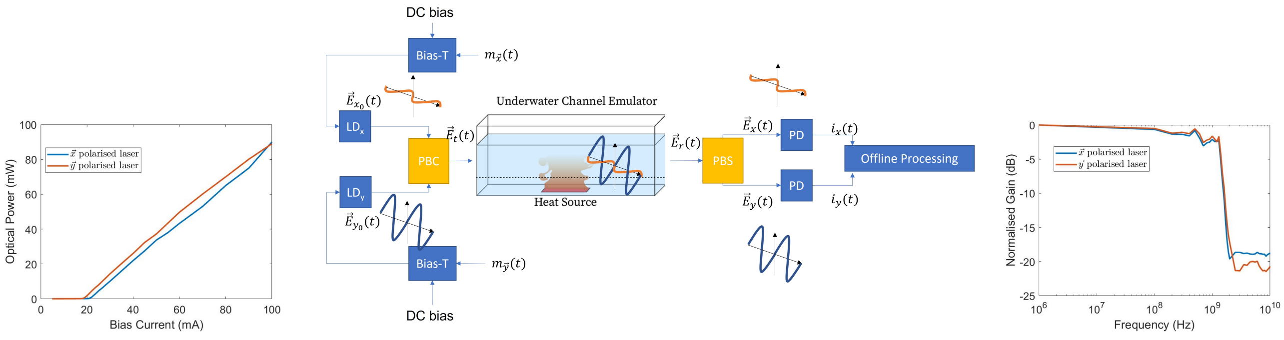
In natural waters the composition of the channel is not constant. Inhomogeneities within the water composition yield fluctuations in refractive index over the length of the channel.[4] This in turn, causes photons to deviate from their direct path and the optical power incident on the receiver (Rx) fluctuates. This effect is known as turbulence induced fading and is characterised in terms of the variance of the incoming signal by the scintillation index, σ_I^2, where:[1]

$$\sigma_I^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}, \tag{2}$$

where I is the received intensity and $\langle . \rangle$ denotes the ensemble average.

The subcarrier intensity modulation (SIM) technique has been found to provide a resilience to the effects of turbulence induced fading by encoding data upon the phase, as well as the amplitude, of the transmitted subcarrier signal.[5] In our previous work on SIM, it was found that the highest data rates were achieved using SIM modulated with quadrature amplitude modulation (QAM).[5] The data rate of QAM-SIM could then be further optimised by applying the bit and power loading (BPL) technique, as in.[6] Further to the properties of the carrier signal, the properties of light itself can be exploited as additional degrees of freedom for data transmission. One such property is the polarisation state, that is the direction of oscillation in the transverse optical wave. The polarisation state is exploited to transmit data across two orthogonally polarised channels in a technique called polarisation division multiplexing (PDM). The two techniques can be combined to form SIM-PDM and increase the spectral efficiency by transmitting data independently across two polarisation states, as in reference.[7] In this paper, we demonstrate the performance of the QAM-SIM-PDM technique in hostile UOWC channel conditions that may be present in any practical application of the technology.

2. EXPERIMENTAL SETUP AND RESULTS



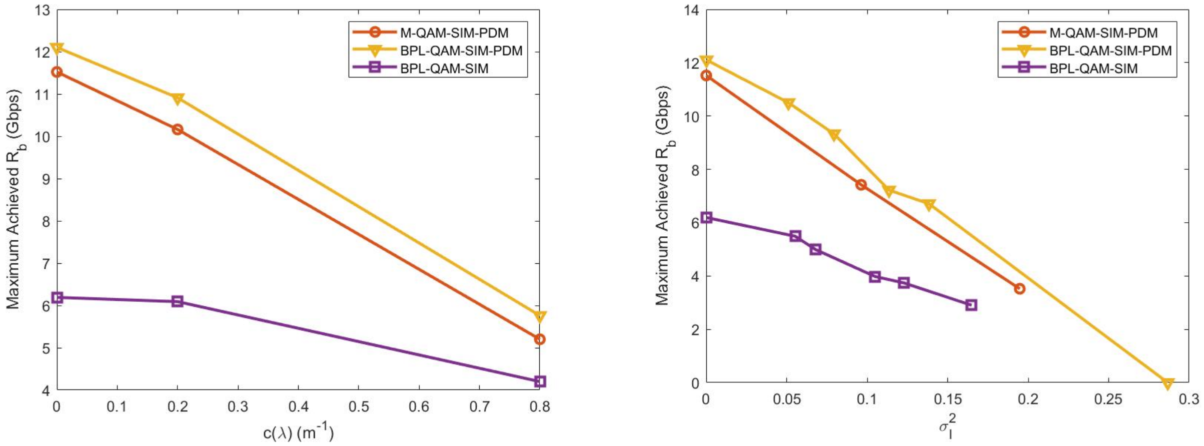
(a) (b) (c)

Figure 1: Experimental setup and preliminary link characterisation.

Figure 1 displays the system block diagram along with the power against bias current and frequency response plots for the two polarisation states. The system block diagram is shown in Fig. 1b, where it can be seen that two orthogonally polarised Osram PL450b laser diodes (LD) are separately modulated and combined via a Thorlabs PBS251/M prism, operating as a polarisation beam combiner (PBC), prior to transmission through the underwater channel emulator (UCE). The UCE is the same as that used in our previous work, including references.[5,8] The channel conditions within the UCE can be controlled by adding crushed antacid tablets to increase turbidity, or by applying a temperature inhomogeneity to generate turbulence. After propagating the UCE, the received signal is then split back in to its constituent polarisation states by a Thorlabs PBS251/M operating as a polarisation beam splitter. The two optical signals are then recovered by two identical Femto HSPR-X-I-1G4-SI photodiodes (PD) and sampled using an Agilent DSA90804A for offline processing.

In Fig. 1a it is shown that both laser diodes display a high degree of linearity but have different threshold currents. This must be accounted for when selecting the bias currents for the rest of this study to ensure the signal-to-noise-ratio (SNR) of each polarisation state is equal. Similarly, it is shown in Fig. 1c that frequency response of the two orthogonally polarised links are approximately identical, with a 3 dB bandwidth above 1 GHz. The mean received SNR in still/clear water is measured to be around 20 dB for both orthogonally polarised channels.

The channel effects generated within the UCE must be classified prior to data transmission. First, the channel coefficients $a(\lambda)$ and $c(\lambda)$ were calculated directly from the received optical power, with $b(\lambda)$ estimated using (1). The two turbid case study channels have coefficients: $a(\lambda) = 0.08$ m^{-1}, $b(\lambda) = 0.12$ m^{-1} and $c(\lambda) = 0.2$ m^{-1}; and $a(\lambda) = 0.3$ m^{-1}, $b(\lambda) = 0.5$ m^{-1} and $c(\lambda) = 0.8$ m^{-1}. In terms of absorption, the turbid condition 1 roughly corresponds to Jerlov type IC, whilst turbid condition 2 corresponds to type 5C. The antacid particles used in this study have a lower scattering coefficient than the particles suspended in ocean waters measured by Jerlov as evidenced by the estimated $b(\lambda)$ being lower than those calculated from Jerlov's measurements for conditions with a similar $a(\lambda)$. As turbulence is a random process it is measured simultaneously with data transmission by recording the peak-to-peak voltage (V_{PP}) of a 25 MHz frequency square wave pilot sequence. This pilot and data transmission is repeated for 500 iterations and the V_{PP} is used to estimate σ_I^2 using (2).



(a) The turbid channel.

(b) The turbulent channel.

Figure 2: The maximum data rate achieved within the FEC limit under hostile channel conditions.

The performance of data transmission using QAM-SIM-PDM is next investigated in turbid and turbulent UOWC channels. Two data streams are independently modulated with QAM-SIM off-line in Matlab and transmitted via a Keysight M8195A arbitrary waveform generator (AWG) with a $V_{\mathrm{PP}} = 0.5$ V. In Figure 2, the maximum data rate, R_b, achievable below the forward error correction (FEC) limit is plotted against both $c(\lambda)$ and σ_I^2 to evaluate the performance of SIM-PDM in hostile channel conditions. When the BER of a system is below the FEC then error correction codes can be applied to make the transmission in effect error free. Thus, it provides a good metric for which to compare modulation techniques in different channels. It can be seen that in clear/still waters ($c(\lambda) = 0$ m^{-1}/$\sigma_I^2 = 0$) the maximum data rate achievable using M-QAM-SIM-PDM is approximately 11.5 Gbps. This data rate is further optimised to the channel response using the BPL technique to achieve 12.1 Gbps. In contrast, the data rate achievable using conventional BPL-QAM-SIM is 6.2 Gbps, confirming the expected increase in throughput by using PDM. It would have been expected that the achievable data rate of BPL-QAM-SIM-PDM would be double that of BPL-QAM-SIM but the recorded increase is slightly below this, which can be attributed to minor differences in alignment between the two orthogonally polarised channels.

Figure 2a shows the maximum R_b achieved in different conditions of turbidity. Compared to the clear water channel, the data rate achieved using M-QAM-SIM-PDM decreased by about 12% to 10.2 Gbps in turbid condition 1 and 55% to 5.2 Gbps in turbid condition 2. This is in line with the expectation that the received SNR will decrease as turbidity increases. Similarly to the clear water channel, the BPL technique is applied in turbid water. Again, it is seen to provide an increase in achievable data rate in all channel conditions considered. Yielding data rates of 10.9 Gbps and 5.8 Gbps in turbid conditions 1 and 2, respectively.

Figure 2b displays the maximum R_b achieved in the presence of turbulence. Due to the random nature of turbulence, it is impossible to compare modulation techniques in identical channels, but the overall trend can be seen that the achievable R_b decreases as σ_I^2 increases. Again, the highest data rates, in all channel conditions considered, are achieved using BPL-QAM-SIM-PDM. At a $\sigma_I^2 \approx 0.05$, a data rate of 10.5 Gbps is achieved with BPL-QAM-SIM-PDM compared to 5.5 Gbps using the BPL-QAM-SIM technique. This shows that the increase in R_b due to applying PDM is maintained even under turbulent channel conditions.

3. CONCLUSION

The results presented within this paper demonstrate the performance of the QAM-SIM-PDM technique under hostile channel conditions for UOWC. Using QAM-SIM-PDM it is shown that data rates beyond 10 Gbps can be achieved in clear and still UOWC channel conditions, with Gbps data rates maintained even in turbid and turbulent conditions. It is further shown that by exploiting the polarisation state for multiplexing, the data rates achievable using QAM-SIM can be approximately doubled in all channel conditions.

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