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

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Abstract—This paper describes the empirical evaluation of polarisation division multiplexing (PDM) as a means to increase the spectral efficiency of subcarrier intensity modulation (SIM) in underwater optical wireless communications (UOWC). The UOWC channel is first characterised in order to gain an understanding of the effect of the water conditions under consideration on the propagating optical signal. Then the performance of SIM-PDM is investigated under turbulent and turbid channel conditions in terms of bit error rate (BER) and maximum data rate. Using SIM-PDM along with quadrature amplitude modulation (QAM) and the bit and power loading (BPL) technique, a maximum data rate of 12.1 Gbps is achieved in a still water channel whilst rates of 10 Gbps are maintained in turbulent and turbid water conditions.

I. INTRODUCTION

Underwater optical wireless communications (UOWC) is a technology that uses light waves to transmit information within aquatic environments. This emerging technology has the potential to provide high data rates with low latency over relatively short link distances (10s of metres) in the underwater environment compared to the dominant underwater acoustic techniques [1]. However, natural phenomena within the underwater channel affect photon propagation and limit the performance of UOWC. The effect of these channel conditions must be understood and overcome before UOWC can be reliably implemented in a real-world setting. In this paper, two channel effects are considered, they are turbulence and turbidity. These represent distinct UOWC channel characteristics inherent in real-world waters that cause the incoming signal to degrade compared to the case of still water. Therefore, advanced signalling techniques should be applied to optimise the transmission for the UOWC channel. In this work, we utilise subcarrier intensity modulation (SIM), which has been shown in our previous work to provide a degree of resilience to the effects of turbulence, in conjunction with polarisation division multiplexing (PDM) to achieve data rates greater than 10 Gbps under hostile UOWC channel conditions.

II. RELATION TO THE LITERATURE AND CONTRIBUTIONS

Existing literature on UOWC has extensively covered the effect of underwater turbulence on the amplitude of the received signal, including in [2]–[5]. Similarly, the effect of turbidity on the optical signal has been investigated in detail, including references [6]–[9]. Where [9] empirically studied the effect of turbid water on the polarisation of a received signal in UOWC. The effect of turbulence on the polarisation of propagating light has been studied in [10], [11] where the results indicate that the polarisation properties are broadly maintained over 10’s of metres. However, to the best of the authors knowledge, there exists no empirical study that considers the effect of underwater turbulence on the polarisation of propagating light with a focus on applications in UOWC. This paper aims to fill that gap in literature by presenting an empirical study into the effect of turbulence, along with turbidity, on the polarisation of a received UOWC signal.

Data rates exceeding 10 Gbps have been reported UOWC literature, including 50 Gbps over a 2.5 m link with a water-air-water interface in [12], and 30 Gbps in still water over an 12.5 m link in [13], both using 4-PAM. In [13] the effect of turbidity on transmission was also investigated with 15 Gbps achieved over 2.5 m in water with an extinction coefficient of 2.525 m^{-1}. SIM-based techniques, such as orthogonal frequency division multiplexing (OFDM), have been utilised to implement the spectrally efficient quadrature amplitude modulation (QAM) scheme to achieve data rates in excess of 10 Gbps [14], [15]. The bit and power loading (BPL) technique has then been used to further optimise the performance of QAM-SIM techniques [16], [17]. In [18], multiplexing is used to further increase the achievable data rate beyond 25 Gbps, using PDM along with wavelength division multiplexing (WDM) in still water using OFDM to modulate QAM-OFDM onto 4 independent channels. Our prior work in [17] detailed a comparison of modulation schemes, including PAM and QAM-SIM, in turbulent water conditions over a 1.5 m link. It was shown that PAM is unsuited to use in the presence of turbulence, whereas QAM-SIM allowed for high data rate links even under turbulent conditions. The maximum data rate achieved with QAM-SIM was 4.2 Gbps in still water, and in water with scintillation index, \( \sigma_2^2 \approx 0.14 \). The polarisation properties of light were exploited to provide a resilience to the effects of underwater turbulence using coherent polarisation-shift keying (PolSK) in [19]. The data transmission results documented in this paper build on those of our previous work in reference [17] and the PDM technique used in reference [18] to demonstrate the applicability of SIM-PDM for high-speed UOWC in hostile water conditions. We also achieve a new state-of-the-art data rate for the turbulent channel using QAM-SIM-PDM.
III. The Underwater Optical Wireless Channel

One important UOWC channel effect is turbulence. This is caused by variations in the water composition, such as inhomogeneities in temperature or salinity, that in turn yield variations in refractive index along the link [20]. These variations in refractive index cause the photon beam to deviate from its initial alignment, resulting in the received optical power to fluctuate over time. This fluctuation in optical power is termed turbulence induced fading and can be quantified in terms of the scintillation index, $\sigma_i^2$, defined as [1]:

$$\sigma_i^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}$$

where $I$ is the received intensity and $\langle \cdot \rangle$ denotes the ensemble average. Previous studies have found that the generalised-Gamma distribution (GGD) can provide a good fit to the received intensity distribution due to turbulence induced fading in UOWC channels [4], [21]. The variance of fluctuations in the received signal is one aspect of turbulence, the channel coherence time is another important aspect to consider when designing a communication system. That is, the shortest time for which the channel gain due to turbulence induced fading is constant. This is defined as the shortest time difference between two channel realisations that are correlated. The coherence time of a turbulent UOWC channel has been investigated analytically in [22] and through experimental studies in [5], [19].

Turbidity is a measure of the clarity of water and is described in terms of the inherent optical properties (IOP) [23]. They are, the absorption and scattering properties of the UOWC channel. When photons propagate through water, they are subject to scattering and absorption, dependent upon the composition and condition of the water medium [1]. Absorption occurs when an interaction with a particle causes the energy of a propagating photon to be lost. Thus, the photon stops propagating - meaning absorption causes an attenuation in the received optical power. Conversely, scattering occurs when the trajectory of a propagating photon is altered upon interaction with a particle [23]. Scattering causes a greater spatial dispersion of the photon beam, and in the case of a multiple scattering channel an increase in temporal dispersion too [6], [7], [24], [25].

The received signal in a UOWC system using intensity modulation with direct detection (IM/DD) transmitted through a channel containing sources of turbulence and turbidity is given by [26]:

$$y(t) = \kappa R P_t(t) \ast h(t) + n(t),$$

where, $P_t(t)$ is the transmitted signal power at time $t$, $R$ is the responsivity of the photodetector, and $n(t)$ is additive noise. In this model, the effect of absorption and scattering on the signal is represented by the channel impulse response, $h(t)$. While the fluctuations in the incoming signal due to the effect of turbulence is described by the fading coefficient, $\kappa$.

IV. Subcarrier Intensity Modulation with Polarisation Division Multiplexing

The IM/DD transmitted optical power, $P_t(t)$, is given by [26]:

$$P_t(t) = P_{av}(1 + \beta m(t)),$$

where $P_{av}$ is the average transmitted optical power, $\beta$ is the modulation index, and $m(t)$ is the time continuous modulated signal. It is evident from (2) that information encoded on the amplitude of $m(t)$ would be susceptible to turbulence induced fading. Therefore, encoding data on other characteristics of the carrier wave can shield it from the effects of turbulence. Similarly, in multiple scattering channels, where $h(t)$ has a large delay spread, spectrally efficient modulation techniques should be used to overcome the bandwidth limitation introduced by the UOWC channel.

SIM is a multi-carrier technique that allows data to be encoded upon the frequency, $f_i$, and phase, $\phi_i$ of a subcarrier signal as well as the amplitude, $A_i$. The subcarrier signal is in turn used to modulate the intensity of the optical signal. Where $m(t)$ is given by [26]:

$$m(t) = \sum_{i=1}^{N} A_i \cos(2\pi f_i t + \phi_i).$$

In SIM, data that is encoded on the phase or frequency of the subcarrier signal is shielded from the effects of turbulence induced fading. This resilience to turbulence has been demonstrated experimentally in our earlier works when SIM was used to implement frequency-shift keying (FSK), phase-shift keying (PSK), and QAM [17], [27], [28]. In [17] it was found that although some data is encoded on the amplitude in QAM-SIM, the reduction in SNR requirements from modulating across 2-dimensions means higher data rates than when using PSK-SIM can be achieved, even in the presence of turbulence. Additionally, the data rate of a QAM-SIM system can be optimised using the BPL technique. Here rather than applying a constant modulation order, $M$, to all subcarriers, each subcarrier is assigned a value of $M$ calculated to meet a target BER (BERTarget) based on that subcarriers SNR, as in [29].

As well as encoding data on characteristics of the subcarrier signal, it is possible to make use of the properties of the optical signal itself. One such property is the polarisation state of the transmitted optical signal [30]. When photons are scattered, their polarisation state is altered, with this change being related to the scattering angle [31]. This has been observed experimentally in [32] where it was shown that there is a negligible change in the polarisation characteristics of light after a small angle scattering interaction of less than 10°. Thus, the polarisation state of incoming light is shielded from the effects of small angle scattering from underwater turbulence as well as single scattering due to suspended particles provided the light source is not divergent and the receiver is aligned with the original trajectory of the optical beam. In situ measurements have demonstrated this in real-world conditions, showing the polarisation state is maintained over 10’s of metres link distance [9], [33], in agreement with the analytical studies in [10], [11]. Polarisation properties
of the underwater channel have been exploited to improve performance in underwater imaging and LIDAR by discriminating between scattered and unscattered photons [34]–[36]. In UOWC, the polarisation state can be exploited as either an additional dimension of the signal to encode data, as in PolSK [19], [37]; or to separate independent data streams, as in PDM [18]; or as a means to suppress interference from scattered light [38].

In this study, we exploit the polarisation property of light to increase the spectral efficiency of UOWC transmission by encoding data over orthogonally polarised light beams using PDM. The PDM technique is applied in conjunction with SIM modulation to form SIM-PDM, thereby doubling the data rate achievable using conventional SIM. Here, two independently modulated SIM data streams are transmitted via two laser diodes, respectively polarised in \( x \) and \( y \) direction. A benefit of this is that, in practical applications, PDM may be implemented by simply combining two UOWC transceivers - with some additional optics. This doubles the achievable data rate whilst utilising existing system architecture and creating a flexible system that can be easily adapted or retrofitted to meet the current link requirements. Here, the transmitted optical signal can be written as:

\[
\vec{E}_t(t) = \exp\left[j(\omega t + \phi)\right] \left[\sqrt{P_{tx}^x(t)}\vec{x} + \sqrt{P_{tx}^y(t)}\vec{y}\right].
\]  

Where the exponential term describes the optical carrier with angular frequency, \( \omega = \frac{2\pi}{\lambda} \), where \( c \) is the speed of light and \( \lambda \) is the wavelength of the optical carrier and phase, \( \phi \). The data is encoded independently via intensity modulation on the optical power of each polarisation state, \( P_{tx}^x(t) \) and \( P_{tx}^y(t) \), using (3). The transmitted light beam, made up of both \( x \) and \( y \) polarisation states, then propagates through the UOWC channel described by (2). At the receiver, a polarisation beam splitter (PBS) is used to separate the incoming optical carrier into its constituent \( x \) and \( y \) polarisation states. As illustrated in Fig. 1c, these two intensity modulated optical signals are then recovered using direct detection and decoded as independent SIM-modulated signals.

V. EXPERIMENTAL TEST-BED AND UNDERWATER CHANNEL EMULATOR

A block diagram of the experimental test-bed used in this study is shown in Fig. 1, along with the optical power vs DC bias current curve, and frequency response of the link. The preliminary link characterisation is used to inform the set-up of the test-bed in subsequent parts of this study. In Figure 1a it is shown that both Osram PL450b laser diodes (LD) exhibit a high degree of linearity, making them suitable for intensity modulation. However, they have different threshold currents that must be accounted for when selecting the DC bias. It was found that light emitted by the PL450b LD is linearly polarised. Therefore, by positioning two identical LDs such that they have a difference in rotation angle of 90° they can be made to be orthogonally polarised relative to each other. In Figure 1b, it can be seen that these two orthogonally polarised links have a near identical frequency response with 3 dB bandwidth greater than 1 GHz. This bandwidth limitation is primarily caused by the PDs used in the system. This places an ultimate limit on the achievable data rate in our current set up. The mean received electrical signal-to-noise-ratio (SNR) of both polarisation states is measured to be approximately 20 dB in still water.

Using the experimental test-bed depicted in Fig. 1c, random data is generated and modulated off-line in Matlab using the modulation schemes considered in this study. In the PDM system used in this study, two random data streams are generated offline, in Matlab, and modulated independently using the SIM technique. These two intensity modulated data streams are then sent to the Keysight m8195a arbitrary waveform generator (AWG) where they are converted into two time continuous signals. The two signals are then transmitted from the AWG through two orthogonally polarised Osram PL450b LDs operating at a wavelength of 450 nm with a peak-to-peak voltage (Vpp) of 0.5 V. A DC current is added via a bias-T to ensure that both LDs operate above their respective threshold currents throughout the transmission. The bias current of each LD is selected such that the mean optical transmit power is approximately 20 mW. The emitted light from each orthogonally polarised LD is collimated before being combined into a single beam, using a Thorlabs PBS251/M as a polarisation beam combiner (PBC), prior to transmission through the UCE. After propagating through the UCE, the two orthogonally polarised signals are split back into separate beams, using a Thorlabs PBS251/M as a PBS, and recovered using two identical Femto HSPR-X-I-1G4-S1 photodiodes (PD). These PDs have a photosensitivity of approximately 0.16 A/W at 450 nm. For the study of the turbulent channel, the PDs are used with no lens in order to maximise the effect of turbulence induced fading on the incoming signal (i.e. no aperture averaging). The two
resulting electrical signals are then sampled using an Agilent DSA90804A oscilloscope and processed offline in Matlab.

The UCE consists of a large water tank with dimensions $1.5 \times 0.5 \times 0.5$ m$^3$ and is filled with 225 l of tap water, in which the channel conditions can be controlled. The turbidity of the water within the UCE is controlled by mixing antacid particles into clean tap water within the tank. Whereas, a temperature inhomogeneity is applied by controlling the heat source to generate turbulence within the link. In this work, the temperature inhomogeneity is generated in the centre of the tank, perpendicular to the propagation path of the collimated laser beam. The temperature of the heat source is adjustable so that the strength of turbulence generated may be controlled, allowing us to examine a range of turbulence strengths. The UCE is operated within a laboratory setting, under ambient light conditions.

VI. UOWC CHANNEL CHARACTERISATION

The hostile channel effects generated within the UCE are first characterised prior to data transmission. This section details the characterisation of the turbulence and turbidity generated within the laboratory using the UCE.

A. Turbulent Channel Coherence Time

In order to experimentally investigate the channel coherence time, the channel must be observed over a long period time. In this part of the study, the experimental test-bed is set up with only the on-axis (i.e. $y$-polarised) link while the oscilloscope sample rate is reduced to 500 ksam/s and with a memory depth, $N$, equal to 10 Msam, yielding a total observation window of 20 s. The channel is sampled and the correlation between the original time series channel observation, $y(t)$ - as in (2) - and itself with a time shift, $\Delta t$, is investigated. This comparison is done using the correlation coefficient, given by [39]:

$$\rho(A, B) = \frac{1}{N-1} \sum_{i=1}^{N} \left( \frac{A_i - \mu_A}{\sigma_A} \right) \left( \frac{B_i - \mu_B}{\sigma_B} \right)$$

where $A_i$ and $B_i$ are the $i^{th}$ samples of the two discrete variables under test, and $\mu_{A,B}$ and $\sigma_{A,B}$ are their respective mean and standard deviation. When $\rho(A, B) = 0$ it indicates two random variables are independent of each-other, and when $\rho(A, B) = 1$ the random variables are highly correlated indicating they are linked.

The correlation coefficient between $y(t)$ and its delayed self, $\rho(y(t), y(t + \Delta t))$, calculated over $0 \leq \Delta t \leq 10$ s is plotted against $\Delta t$ in Figure 2 for 5 channel realisations. When $\Delta t = 0$ s, the two time series sequences, $y(t)$ and $y(t + \Delta t)$, are identical so $\rho(y(t), y(t + \Delta t)) = 1$. For all channel realisations, as $\Delta t$ increases the correlation between $y(t)$ and $y(t + \Delta t)$ reduces until $\rho(y(t), y(t + \Delta t))$ fluctuates around 0 for $\Delta t > 1$ s. Using the time at which $\rho(y(t), y(t + \Delta t))$ falls by 3 dB as the point where the channel is no-longer correlated with its delayed counterpart, the channel coherence time is found.

The coherence time found using this technique - along with the corresponding $\sigma^2_y$ calculated for $y(t)$ using (1) - for the five channel realisations in Figure 2 are displayed in the legend. For the channel realisations investigated, the coherence time is in the order of 100 ms with the exception of the strongest turbulence ($\sigma^2_y = 0.1702$) which has a shorter coherence time. This is expected as the higher the $\sigma^2_y$, the more the channel is fluctuating. Nevertheless, it is shown that the channel is stable for the duration of transmission for the typical symbol rates used in UOWC. Resultantly, in order to characterise the channel for data transmission, it should be realised over a number of iterations to account for the slow fading random nature of the turbulent UOWC channel.

B. Scintillation Index and Temperature Inhomogeneity

Following the investigation of channel coherence time, $\sigma^2_y$ is evaluated by sampling the channel over 1000 iterations, each of 200 ksam, at a sample rate of 40 Gsam/s using the test-bed described in Fig. 1. At this sample rate, the AC coupling and high-pass filter nature of the oscilloscope means that the DC component is removed from the incoming signal. To overcome this, a 25 MHz square-wave is transmitted through the channel and the peak-to-peak voltage, $V_{pp}$, is then used to calculate $\sigma^2_y$, as in (1).

Figure 3 shows the empirically measured $\sigma^2_y$ of both $\vec{x}$ and $\vec{y}$ polarisation states plotted against the temperature difference between the turbulent region and the rest of the channel, $\Delta T$. It can be seen that as $\Delta T$ increases, so too does $\sigma^2_y$ until it reaches a plateau at approximately $\sigma^2_y = 0.35$. When there is no temperature inhomogeneity within the channel, $\sigma^2_y \approx 10^{-4}$ which can be considered a still water channel. Here, the variance in the received signal is dominated by additive Gaussian noise. As $\Delta T$ increases beyond 2 K, then $\sigma^2_y$ is larger than $10^{-2}$. In this case, the main source of variance in the incoming signal is due to turbulence. All of the $\sigma^2_y$ observed here are below 1, indicating that the turbulence generated within the UCE in within the weak turbulence regime. It can further be noted that over the two orthogonally polarised links, for a given $\Delta T$ the $\sigma^2_y$ is similar.

Histograms of the received $V_{pp}$ samples for both $\vec{x}$ and $\vec{y}$ polarisation states in still and turbulent water conditions,
respectively fitted with the Gaussian and GGD distributions, are displayed in Fig. 4. The goodness of fit is measured using the coefficient of determination, $R^2$. The measured and fitted $\sigma_f^2$ as well as other parameters of the fitted functions (i.e. the mean of the Gaussian distribution, $m$, and the fitting parameters of GGD, $\alpha$; $\delta$; and $\rho$) and corresponding $R^2$ value can be found in Table I along with the temperature gradient, $\Delta T$, that induced the turbulence within the UCE. It can be seen in Fig. 4a and 4c that in still water ($\sigma_f^2 \approx 10^{-4}$) the received voltage distributions of both polarisation states have a Gaussian shape, centred around a mean of 1. However as $\sigma_f^2$ increases, the distribution shapes become skewed to the right. In the presence of turbulence, it can be seen that the distributions no longer have a Gaussian shape and the GGD provides a better fit.

In Fig. 3, there is a small difference in the measured $\sigma_f^2$ over the two polarisation states. Similarly, the distributions in Fig. 4 have a similar shape and $\sigma_f^2$ for $\vec{x}$ and $\vec{y}$ but are not exactly the same. These observed differences can be attributed to different beam shapes owing to the orientation of the LD in the mount to control the polarisation states and the elliptical footprint of light emitted from the PL450b.

**TABLE I: Fit parameters for Fig. 4**

<table>
<thead>
<tr>
<th>Fit</th>
<th>$\sigma_f^2$</th>
<th>Other parameters</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\vec{x}$, Still water, $\Delta T = 0.4$ K, $\sigma_{\text{meas}} = 1.50 \times 10^{-4}$</td>
<td>Gaussian</td>
<td>$m = 1.00$</td>
<td>0.96</td>
</tr>
<tr>
<td>$\vec{y}$, Still water, $\Delta T = 0.4$ K, $\sigma_{\text{meas}} = 1.14 \times 10^{-4}$</td>
<td>Gaussian</td>
<td>$m = 1.00$</td>
<td>0.97</td>
</tr>
<tr>
<td>$\vec{x}$, Turbulent water, $\Delta T = 6.6$ K, $\sigma_{\text{meas}} = 0.3348$</td>
<td>GGD</td>
<td>$\alpha = 1.53$, $\delta = 0.93$, $\rho = 1.18$</td>
<td>0.96</td>
</tr>
<tr>
<td>$\vec{y}$, Turbulent water, $\Delta T = 6.6$ K, $\sigma_{\text{meas}} = 0.3127$</td>
<td>GGD</td>
<td>$\alpha = 2.98$, $\delta = 1.36$, $\rho = 0.53$</td>
<td>0.96</td>
</tr>
</tbody>
</table>

### C. Effect of the UOWC Channel on Polarisation

The effect of the UOWC channel on the polarisation properties of light should be investigated to confirm that it is practical to utilise this property for UOWC applications. For this part of the study, the experimental test-bed in Fig. 1 is used with the PBC removed and a single laser source in the on-axis position transmitting light directly into the water tank. This LD is rotated such that the emitted light is linearly polarised with a degree of polarisation (DoP) of approximately 80%. After propagating through the UCE, the effect of the UOWC channel on polarisation is observed by comparing the received DoP in different channel conditions. The DoP is given by [9]:

$$\text{DoP} = \frac{V_{PP}^\vec{y} - V_{PP}^\vec{x}}{V_{PP}^\vec{y} + V_{PP}^\vec{x}} \times 100\%$$

(7)

First, the effect of underwater turbulence on the polarisation states of the received optical signal is investigated over 1000 channel realisations, with the results displayed in Fig. 5. In Fig. 5a, it can be seen that the mean received DoP remains relatively stable, at around 80%, even as $\sigma_f^2$ increases. Indicating that the amplitude of the two polarisation states remains the same after propagating through the turbulent channel.

In Fig. 3, there is a small difference in the measured $\sigma_f^2$ over the two polarisation states. Similarly, the distributions in Fig. 4 have a similar shape and $\sigma_f^2$ for $\vec{x}$ and $\vec{y}$ but are not exactly the same. These observed differences can be attributed to different beam shapes owing to the orientation of the LD in the mount to control the polarisation states and the elliptical footprint of light emitted from the PL450b.
PDM signals carried on the states are corrupted. In a turbulent UOWC channel, the received signal will fluctuate in line with the channel gain, as described in (2). Therefore, the effect of underwater turbulence on the polarisation characteristics of light can also be evaluated by observing the similarity of the two polarisation states contained within the propagating optical beam. Using $\rho(V_{pp}^\gamma, V_{pp}^\gamma)$, the correlation between the two polarisation states may be observed. If turbulence induced scattering is affecting both polarisation states equally, then the correlation coefficient between the two signals would be equal to 1. However, if the channel was altering the polarisation characteristics of the propagating light $\rho(V_{pp}^\gamma, V_{pp}^\gamma)$ would be negative as amplitudes of the received signals would fluctuate oppositely. In Fig. 5b, it can be seen that in still water, when $\sigma^2 \approx 10^{-4}$, then $\rho(V_{pp}^\gamma, V_{pp}^\gamma) \approx 0$ as would be expected in a noise dominated channel. As $\sigma^2$ increases and fluctuations due to turbulence begin to dominate the channel, then $\rho(V_{pp}^\gamma, V_{pp}^\gamma)$ increases towards 1. The results presented in Fig. 5 confirm that the polarisation states of received optical signals are maintained after propagating though the turbulent channel generated within the UCE. Thus, empirically confirming that the PDM technique is applicable for a turbulent UOWC channel, and inline with the expectation that the polarisation characteristics are maintained after a photon undergoes a small angle, single scattering interaction, such as turbulence induced scattering.

Next, the effect of turbidity on the polarisation properties of the received signal is investigated. Prior to examining the DoP, the turbid propagation coefficients must be measured in order to quantify the turbidity generated within the UCE. The propagation coefficients (absorption, scattering, and extinction) calculated from the received optical power are presented for a range of antacid concentrations in Fig. 6a. Here, the absorption and extinction coefficients, $a(\lambda)$ and $c(\lambda)$ respectively, are estimated directly using a test-bed similar to the one used to measure the turbulent channel coherence time, but with a Thorlabs PM100USB optical power meter in place of the PD. When measuring the received power to estimate $a(\lambda)$ a lens with a diameter of 4.5 cm, providing a maximum gain of 35 dB, is placed in front of the power meter so that a large proportion of scattered photons are still incident on the receiver. Thus, the decrease in received optical power will be primarily due to absorption. Conversely, $c(\lambda)$ is found by placing a 3 mm pin-hole in front of the power meter so that both scattered and absorbed photons are lost to the receiver. Then the scattering coefficient, $b(\lambda)$, can be found indirectly by $b(\lambda) = c(\lambda) - a(\lambda)$ to provide a reasonable estimate for all three IOP propagation coefficients, as described in references [23], [40]. In Fig. 6a, the calculated coefficients are plotted against the antacid concentration and fitted with a 3rd order polynomial curve to reduce the effect of experimental variations in the measurement process, as in [40]. It can be seen that as the antacid concentration within the UCE increases, the propagation coefficients increase approximately linearly up to approximately 20 mg/L. Beyond this point, the product of $b(\lambda)$ and the link distance ($Z_{link} = 1.5$ m) exceeds 1, indicating multiple scattering interactions are taking place within the channel. Under these conditions, the method of estimating the propagation coefficients is inaccurate as multiply scattered photons are lost to the measurement of $a(\lambda)$ resulting in the absorption component of the channel being overstated, as illustrated by the upward inflection in the fitted $a(\lambda)$ curve in Fig. 6a. Resultantly, the channel coefficients measured using this technique are only reliable for the single scattering condition, $b(\lambda)Z_{link} < 1$.

In Fig. 6b, the observed DoP is plotted against $c(\lambda)$ - as estimated using the fitted polynomial in Fig. 6a. For this study, the test-bed is set up in the same way as it was for the investigation into the effect of turbulence on the DoP, but with antacid powder added to the water and no temperature inhomogeneity applied within the UCE. It can be seen that up for $c(\lambda) < 0.8$ m$^{-1}$, the DoP remains approximately 80%. The fluctuations in the DoP can be attributed to changes in SNR as the received optical power falls, resulting in the voltage scale of the oscilloscope to be changed and the quantisation noise floor alter accordingly. Beyond $c(\lambda) = 0.8$ m$^{-1}$, the DoP appears to fall steeply as $V_{pp}^\gamma$ is at the noise floor of the oscilloscope so does not decrease in line with the incident power as $V_{pp}^\gamma$ does. The fact that the DoP remains approximately constant around 80% up to $c(\lambda) = 0.8$ m$^{-1}$ indicates that turbidity has a minimal effect on the polarisation properties of a received optical signal under single scattering UOWC channel conditions. This suggests that polarisation-based data transmission techniques, such as PDM, can be employed in turbid conditions, provided the scattering component of the channel is not too high. This finding is inline with the expectation that under single scattering conditions, the polarisation characteristics of forward scattered photons are maintained in the underwater channel.

VII. DATA TRANSMISSION USING PDM

Following the characterisation of the effect of the UOWC channel on the polarisation properties of the received optical signal, these characteristics are exploited to increase the spectral efficiency of UOWC data transmission. The performance of the modulation techniques under test will be evaluated in terms of the data rate at which they reach the forward error correction (FEC) limit of $3 \times 10^{-3}$. When the BER is below the FEC, channel coding can make transmission effectively error free.

Fig. 6: Figures detailing the relationship between the concentration of antacid particles in the UCE and the turbidity of the UOWC channel (a), and the mean received DoP plotted against the extinction coefficient, $c(\lambda)$ (b).
A. Transmission in Turbulent UOWC

First, the performance of SIM-PDM data transmission is explored under turbulence induced fading channel conditions. Due to the long channel coherence time of turbulence generated within the UCE relative to the symbol rates considered in this study, the channel is stationary over the sampling period of the oscilloscope. Therefore, in order to evaluate the BER performance within the turbulent channel, data packets of \(200 \times 10^3\) samples, sampled at 20 Gsam/s, are transmitted over 500 iterations. The BER is then calculated by averaging over these iterations for both polarisation states. This ensures that the BER converges to a repeatable value for similar channel conditions.

The average system BER (across both \(\vec{x}\) and \(\vec{y}\)) is plotted against symbol rate, \(R_s\), in Fig. 7 for still water and turbulence with \(\sigma_I^2 \approx 0.1\) across the two orthogonally polarised links. In still water, 2-PSK-SIM-PDM reaches the FEC at \(R_s = 1.84\) GSym/s which corresponds to a data rate, \(R_b\), of 3.68 Gbps for the whole system. In the turbulent channel condition, the symbol rate at which FEC is reached decreases to 1.66 GSym/s (3.36 Gbps). This represents a 10.6% drop in data rate, which can be attributed to a reduction in average SNR in the turbulent channel.

![Fig. 7: BER vs \(R_s\) for 2-PSK and \{4,16,64\}-QAM in still and turbulent (\(\sigma_I^2 \approx 0.1\)) waters.](image)

In applications where high data rate is favoured, then higher modulation orders, \(M\), can be employed to improve spectral efficiency. Due to encoding data on the amplitude as well as the phase, QAM has lower SNR requirements than PSK with the same modulation order for \(M > 4\). This makes QAM more suitable for channels with SNR limitations when a high data rate is targeted. Using \{4, 16, 64\}-QAM-SIM-PDM, the symbol rates at which FEC is breached are 1.71 GSym/s, 1.44 GSym/s, and 0.81 GSym/s respectively. These correspond to respective data rates of 6.84 Gbps, 11.52 Gbps, and 9.71 Gbps. In the presence of turbulence, the data rate achievable with 4-QAM-SIM-PDM falls by 22% to 5.32 Gbps and by 35% to 7.42 Gbps for 16-QAM-SIM-PDM, whilst communication with 64-QAM-SIM-PDM is not supported within the FEC limit. It can be noted that for some modulation orders the BER curves exhibit an increase at low symbol rates.

This can be attributed to the high-pass filter nature of the components in the transmitter and receiver (i.e. bias-T, PD, and oscilloscope) causing the lower frequency components of some symbol combinations to be removed.

The maximum \(R_b\) achieved within the FEC limit using these techniques is plotted against \(\sigma_I^2\) in Fig. 8. The commonly used on-off keying (OOK) modulation scheme is also included in Fig. 8 for comparison as a baseline. Using fixed-threshold OOK, a data rate of 2.8 Gbps is supported in still water. Whilst in a turbulent UOWC channel with \(\sigma_I^2 \approx 0.05\) transmission below FEC is not possible, as fluctuations in the received optical signal amplitude cause a breakdown in the decision boundary between OOK modulated symbols. Conversely, Gbps data rates are supported by the SIM-based techniques above \(\sigma_I^2 \approx 0.05\) due to data being encoded on the phase instead of or alongside the amplitude of the subcarrier signal. However, for all modulation techniques under test it can be seen that the achievable data rate decreases as \(\sigma_I^2\) increases, which can be attributed to a reduction in the received SNR associated with turbulence induced fading. Fixed \(M\)-PSK-SIM-PDM can achieve a maximum data rate of 8.9 Gbps in still water with \(M = 16\). Under turbulent conditions, as the average SNR falls, the achievable rates fall to 5.8 Gbps with \(M = 4\) and 3.1 Gbps with \(M = 2\) at \(\sigma_I^2 \approx 0.11\) and 0.14 respectively. Similarly, fixed \(M\)-QAM-SIM-PDM achieves a maximum data rate of 11.5 Gbps in still water, falling to 7.4 Gbps and 3.6 Gbps as \(\sigma_I^2\) increases to approximately 0.1 and 0.2, respectively. When \(\sigma_I^2 \approx 0.1\), the decrease in performance of \(M\)-PSK-SIM-PDM is proportionally lower than that of \(M\)-QAM-SIM-PDM, due to data encoded on the subcarrier phase being shielded from the effects of turbulence. However, as \(\sigma_I^2\) increases towards 0.15 the maximum achieved \(R_b\) of \(M\)-PSK-SIM-PDM experiences a steep drop-off whereas the \(R_b\) of \(M\)-QAM-SIM-PDM maintains a more linear trajectory. This illustrates the resilience to turbulence induced fading due to encoding data on the phase through PSK-SIM, as well as the SNR penalty from utilising only one dimension of the subcarrier. Thus, despite data encoded on the amplitude is...
sustainable to the effects of turbulence, it can be beneficial to use QAM-SIM over PSK-SIM to take advantage of the reduced SNR requirements of multi-dimension modulation.

The maximum data rates achieved with BPL-QAM-SIM-PDM and BPL-QAM-SIM are also displayed in Fig. 8. It is shown that the BPL technique further optimises the performance of QAM-SIM-PDM to increase the achievable data rate to 12.1 Gbps in still water compared to 6.2 Gbps with BPL-QAM-SIM. Under all conditions of turbulence, the data rates achievable using BPL-QAM-SIM-PDM are greater than the fixed-$M$ equivalent. Additionally, for all $\sigma_I^2$, the data rate achieved using BPL-QAM-SIM-PDM is approximately twice that of BPL-QAM-SIM. This confirms the expected increase in spectral efficiency gained by exploiting the polarisation state. This observation that the achievable data rate of BPL-QAM-SIM-PDM is around double that of BPL-QAM-SIM is further evidence that the polarisation state of the optical carrier is not affected by underwater turbulence under the channel conditions considered. Thus confirming the suitability of PDM for use in UOWC applications in turbulent conditions.

The SNR of each subcarrier is estimated from the error vector magnitude of 100 pilot iterations of 4-QAM-SIM-PDM with an $R_s$ of 1.55 GSym/s. BPL is then applied to the QAM-SIM signals on the two orthogonally polarised links. In BPL, the $M$ of each subcarrier is calculated using the assumption of an additive white Gaussian noise (AWGN) channel. Therefore, in a turbulent channel - where variations are not primarily caused by AWGN - the observed BER can be expected to be larger than BER$^{\text{Target}}$. This is illustrated in Fig. 9a where the observed BER is plotted against $\sigma_I^2$ for various values of BER$^{\text{Target}}$. It can be seen that for all BER$^{\text{Target}}$ the observed BER rises with an increase in $\sigma_I^2$. When $\sigma_I^2$ increases, BPL with a BER$^{\text{Target}}$ close to the FEC lacks a margin to account for the increased fluctuations leading to an observed BER greater than the FEC. In order for $\text{BER} = \text{BER}^{\text{Target}}$ the model used in assigning $M$ to each subcarrier would have to better represent the channel. Rather than assuming AWGN some level of channel knowledge should be used to find an appropriate $M$ based on the turbulence characteristics in the channel. However, due to the random nature of turbulence this is impractical as the $\sigma_I^2$ and distribution shape are not stable for the duration of transmission.

The maximum data rate achieved using BPL-QAM-SIM-PDM in different turbulent conditions is shown in Fig 9b. Here, the maximum data rate of 12.1 Gbps is achieved in still water with a BER$^{\text{Target}}$ of $10^{-3}$. Using BER$^{\text{Target}} = 5 \times 10^{-4}$, a data rate of 11.5 Gbps is achieved, whilst BER$^{\text{Target}}$ of $10^{-4}$ and $10^{-6}$ yield 10.1 Gbps and 8.8 Gbps, respectively. As $\sigma_I^2$ increases, the target $R_s$ decreases in line with the corresponding fall in average SNR due to turbulence induced fading. For $\sigma_I^2 \approx 0.05$, the data rate achieved with a BER$^{\text{Target}} = 10^{-3}$ is approximately 9.6 Gbps, compared to 10.5 Gbps with a BER$^{\text{Target}} = 5 \times 10^{-4}$. When $\sigma_I^2$ increases, variance due to turbulence induced fading becomes too large to be accounted for simply as a reduction in average SNR in the BPL algorithm. At this point, communication cannot be supported for BPL at that BER$^{\text{Target}}$ and a lower BER$^{\text{Target}}$ will provide better performance. This can be observed in Fig. 9b where the maximum data rate when $\sigma_I^2 \approx 10^{-4}$ is achieved with BER$^{\text{Target}} = 10^{-3}$, whereas at $\sigma_I^2 \approx 0.05$ the highest data rate is achieved using BER$^{\text{Target}} = 5 \times 10^{-4}$. Similarly, the BER$^{\text{Target}}$ that gives the lowest data rate in the still water channel, BER$^{\text{Target}} = 10^{-6}$, provides the highest data rates in the turbulent channel with $\sigma_I^2 > 0.10$. Indicating that the additional SNR margin is required to account for the effects of turbulence induced fading.

### B. Transmission in Turbid UOWC

![Fig. 10: BER vs $R_s$ for 2-PSK and [4,16,64]-QAM in still and turbid (a) $a(\lambda) = 0.37 \text{ m}^{-1}$, (b) $b(\lambda) = 0.50 \text{ m}^{-1}$, (c) $c(\lambda) = 0.87 \text{ m}^{-1}$ waters.](image)

Finally, the performance of the SIM-PDM techniques are evaluated in turbid UOWC channel conditions. Fig. 10 shows the BER vs symbol rate for 2-PSK-SIM-PDM and QAM-PSK-SIM-PDM with $M = 4, 16$, in clear and turbid water conditions with $a(\lambda) = 0.37 \text{ m}^{-1}$, $b(\lambda) = 0.50 \text{ m}^{-1}$, and $c(\lambda) = 0.87 \text{ m}^{-1}$, which roughly corresponds to the Jerlov IC case study water condition [41]. The clear water BER vs $R_s$ curves are the same as those recorded in still water shown in Fig. 7, as is expected. In the turbid water condition, the maximum symbol rate at which the BER exceeds FEC decreases compared to that of clear water. This is in line with the expectation that the received optical signal after...
propagating a turbid channel will have lower received optical power, and therefore a lower SNR.

Figure 11 shows the maximum $R_b$ achieved in different conditions of turbidity. Again, the OOK modulation technique is included as a baseline to which SIM-PDM is compared. Contrasting with the turbulent conditions, OOK exhibits a degree of resilience to the effects of turbidity as the $R_b = 2.8$ Gbps achieved in clear water is maintained up to $c(\lambda) = 0.2$ m$^{-1}$ in turbid condition 1, before falling by 71% in turbid condition 2 when $c(\lambda) = 0.8$ m$^{-1}$. This is due to low SNR requirement of OOK compared to the SIM-based techniques that utilise multi-level modulation to maximise the achievable data rate. Additionally - unlike the turbulent channel - the turbid channel is stationary, meaning the optimal decoding threshold remains constant throughout the duration of data transmission. Conversely, 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. Similarly to the turbulent water investigation, the BPL technique is applied in turbid water. Similarly to when turbulence was considered, applying BPL to QAM-SIM-PDM is seen to provide an increase in achievable data rate and a slight improvement in the decrease relative to clear water in all channel conditions considered. Yielding data rates of 10.9 Gbps (10% decrease) and 5.8 Gbps (52% decrease) in turbid conditions 1 and 2, respectively by optimising the signal to the available channel SNR. Finally, comparison between BPL-QAM-SIM-PDM and BPL-QAM-SIM shows that, although in clear water the data rate is approximately doubled using PDM, this increase is not maintained as turbidity increases. Referring back to Fig. 6b where it is shown that the DoP is broadly maintained up to $c(\lambda) = 0.8$ m$^{-1}$, this apparent anomaly may instead be attributed to variations in the optical components from the manufacturing process leading to slightly different beam dimensions causing turbidity to have a lesser impact on the performance of the on-axis link. If this was due to a breakdown in received polarisation characteristics the performance of BPL-QAM-SIM-PDM could be expected to be much worse.

In general, Fig. 7 and 10 appear to show that turbulence and turbidity have a similar effect on the performance of UOWC. However, the turbid channel is stable for the whole duration of data transmission. This means that for QAM-SIM implementation, the equaliser can be setup prior to transmission and used so long as the IOP of the channel remain constant. Whereas, the random process of turbulence means the equaliser would need to be updated regularly during transmission in a real-world application.

VIII. Conclusion

In this paper we experimentally demonstrated SIM-PDM for UOWC in hostile water conditions. The channel conditions under consideration where first characterised and the effect of the UOWC channel on the polarisation properties of the received optical signal investigated. It was found that, over the range of $\sigma^2_\lambda$ considered, underwater turbulence had no effect on the polarisation properties of the received optical signal. Similarly, it was found that the polarisation was preserved over the range of turbidities considered up to $c(\lambda) = 0.8$ m$^{-1}$. These results confirm that the polarisation state can be reliably used as an additional dimension for encoding data in UOWC. The polarisation properties were then exploited to implement SIM-PDM and double the achievable data rate compared to conventional SIM techniques in all channel conditions considered. Using BPL-QAM-SIM-PDM, a maximum data rate of 12.1 Gbps was achieved in still/clear water, compared to approximately 6.1 Gbps using BPL-QAM-SIM and 11.6 Gbps achieved with 16-QAM-SIM-PDM. It is further shown that the proportional increase in data rate due to using PDM is maintained over all channel conditions considered. These results demonstrate that the PDM technique may be used in hostile UOWC channel conditions to increase the achievable data rate - or to reduce the link requirements to achieve a given data rate for the application compared to a conventional single link UOWC system - provided the additional complexity and power consumption can be supported within the application.

REFERENCES
