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A Comparison of Modulation Techniques for LED-Based Underwater Optical Wireless Communications

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A thesis submitted for the degree of Master of Philosophy.
The University of Edinburgh.
December 31, 2022

Dedication

Dedication to my dad, Yuanfeng Yu, for his love, care and support.

Lay abstract

Light emitting diode (LED) based underwater optical wireless communications (UOWC) aims to provide high-speed data rates in the underwater environment, which has gotten more attention and developed in recent years to meet the data rate demand for ocean exploration nowadays. Additionally, it offers the advantages of minimal latency and low cost for implementation. It has the potential to be a vital role in the short link in the hybrid underwater network, along with radio frequency (RF) and underwater acoustic communications (UAC) technologies. However, some obstacles need to be overcome, one of the primary challenges is the narrowed modulation bandwidth from the off-the-shelf LEDs that limited the transmission rate. Thus, this thesis is to investigate the performance of high spectral efficiency modulation schemes in various water conditions. The study of the UOWC system, underwater models, equalisation technologies, and experimental data transmission is demonstrated, which contributes to a good understanding of the LED-based UOWC practical application.

Abstract

Light emitting diode (LED) based underwater optical wireless communications (UOWC) aims to provide high-speed data rates in the underwater environment. The field of UOWC has been receiving greater attention in recent years as a viable complementary technology to meet the data rate demands for ocean exploration. It offers a competitive advantage of high-speed, low delay and low cost than radio frequency (RF) and underwater acoustic communications (UAC) technologies in the short-distance underwater link. However, there are still research challenges that need to be overcome, one of the primary challenges is the small modulation bandwidth that limits the transmission rate. This thesis develops a good understanding of the LED-based UOWC applied spectral efficiency modulation schemes as well as the inherent optical properties (IOPs) in underwater conditions.

The thesis begins with an introduction of background for underwater wireless communications (UWC). Comparing the merits of acoustic waves, RF and optical waves. Optical wireless communications (OWC) is superior at high data rates with low latency in medium underwater links (up to 10s of meters), which attracts the researchers' attention and interest. However, UOWC still has some challenges as followed: light suffers from severe absorption and scattering, misalignment of optical transceivers, and reliable underwater devices. To begin with, the UOWC system is described in terms of the optical sources and detectors used. Here, LEDs have been found to be more suitable for certain applications in underwater links than laser diode (LD). Additionally, various modulation schemes and equalisers are used in this thesis to overcome the impairments associated with the limited bandwidth of LED and the resulting inter-symbol interference (ISI) that is stated. Next, the interaction of light and water is described as well as the IOPs measurement. Furthermore, considering the measurement of the natural water environments is difficult, the channel model is commonly used to evaluate the performance of the UOWC transmission. An underwater channel model based on double-gamma function (DGF) is used to investigate the performance of UOWC before experiments are carried out.

Following these, experimental works related to the LED-based UOWC system setup, design of water conditions, the frequency response of LED-based UOWC link, signal-to-noise-ratio (SNR), and results of data transmission are presented. The impact of turbid water conditions on UOWC is experimentally characterised. The performance of pulse amplitude modulation (PAM), carrierless amplitude and phase modulation (CAP), and quadrature amplitude modulation (QAM)-orthogonal frequency division multiplexing (OFDM) is then compared in the previously characterised UOWC channel. These results will contribute to the further development of the LED - based UOWC in realistic channel conditions. In conclusion, the maximum data rates of different modulation schemes are presented. QAM-OFDM has an overall data rate advantage over CAP and PAM but gradually loses the advantage in turbid water conditions. Using QAM-OFDM with bit and power loading (BPL) resulted in a maximum data rate of 557 Mbps in clear water, but CAP has a maximum data rate of 113 Mbps in the most severe turbid water condition considered in this study.

Declaration of originality

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

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Acronyms and abbreviations

APD	avalanche photodiode
AWG	arbitrary waveform generator
AWGN	additive white Gaussian noise
BER	bit-error-rate
BPL	bit and power loading
CP	cyclic prefix
CDOM	coloured dissolved organic material
CAP	carrierless amplitude and phase modulation
DC	direct current
DGF	double-gamma function
DMT	discrete multi-tone
DFE	decision feedback equaliser
DCO-OFDM	direct current biased optical orthogonal frequency division multiplexing
EVM	error vector magnitude
FEC	forward error correction
FPGA	field programmable gate arrays
FIR	finite impulse response
FFT	fast Fourier transform
FSO	free space optical
GaN	Gallium nitride
I/Q	in-phase and quadrature-phase
IM/DD	intensity modulation and direct detection
IOPs	inherent optical properties
IFFT	inverse fast Fourier transforms

ISI	inter-symbol interference
LOS	line-of-sight
LOs	local oscillators
LD	laser diode
LMS	least mean squares
LED	light emitting diode
MC	Monte-Carlo
MLSE	maximum likelihood sequence estimator
MMSE	minimum mean square error
MIMO	multiple input multiple outputs
NRZ	non-return-to-zero
OFDM	orthogonal frequency division multiplexing
OOK	on-off keying
OWC	optical wireless communications
PAM	pulse amplitude modulation
PD	photo detector
PAPR	peak-to-average power ratio
PIN	p-type intrinsic n-type diode
PS	probabilistic-shaping
QAM	quadrature amplitude modulation
RF	radio frequency
RLS	recursive least squares
RMS	root-mean-squared
RC	resistance-capacitance
SRRC	square-root raised-cosine
SNR	signal-to-noise-ratio
sps	samples per symbol
UAC	underwater acoustic communications

UCE	underwater channel emulator
UOWC	underwater optical wireless communications
VD FE	Volterra series-based decision feedback equaliser
V_{pp}	peak-to-peak voltage
WDM	wavelength division multiplexing
UWC	underwater wireless communications
ZFE	zero forcing equaliser

Nomenclatures

$\otimes$	convolution operator
$\exp(.)$	exponential operator
$\lim(.)$	limit operator
$\log_2(.)$	base 2 logarithm
$\sum(.)$	summation operator
$\int(.)$	integration operator
$\ln(.)$	Gradient operator
$Q(.)$	Markov's Q-function
s_k	Mapped symbols
$g_{SRRC}(t)$	square-root raised-cosine filter
$S_{PAM}(t)$	pulse amplitude modulation signal
B_{PAM}	bandwidth of pulse amplitude modulation
β	roll-off factor
D_b	bit rate
m_{PAM}	bits per symbol of pulse amplitude modulation
$h_I(t)$	in-phase filter
$h_Q(t)$	quadrature-phase filter
f_c	center frequency
$S_{CAP}(t)$	carrierless amplitude and phase modulation signal
a_k	real part
b_k	imaginary part
B_{CAP}	bandwidth of carrierless amplitude and phase modulation
m_{CAP}	bits per symbol of carrierless amplitude and phase modulation
η	spectral efficiency
B	bandwidth
B_{OFDM}	bandwidth of orthogonal frequency division multiplexing modulation
N_{sub}	numbers of subcarriers
N_{CP}	number of samples of cyclic prefix
V_{pp}	peak-to-peak voltage

Δr	volume element of water of width
$\Phi_i(\lambda)$	incident light spectral radiant power
$\Phi_a(\lambda)$	absorbed power
$\Phi_s(\lambda)$	scattered power
ψ	scattering direction angle
φ	scattering annular ring
$\Delta\Omega$	solid angle
$\Phi_t(\lambda)$	transmitted power
$A(\lambda)$	absorptance
$B(\lambda)$	scatterance
$a(\lambda)$	absorption coefficient
$b(\lambda)$	scattering coefficient
$c(\lambda)$	attenuation coefficient
λ	wavelength
$\Phi(\lambda)$	magnitude of the power
$h(t)$	impulse response of channel
α	distortion factor
σ_n^2	noise power
κ	electrical-to-optical conversion factor of light-emitting diode
R	responsivity of photodetector
H	channel direct current gain
SNR_{ISI}	signal to interference and noise ratio
BER_{PAM}	bit error rate of pulse amplitude modulation
BER_{QAM}	bit error rate of quadrature amplitude modulation
$y(t)$	received signal
$x(t)$	transmitted signal
$n(t)$	noise
$h_{eq}(t)$	frequency response of zero forcing equaliser
$\hat{X}_i$	output of zero forcing equaliser in frequency domain
Y_i	received signal in frequency domain
$H(f)$	channel frequency response
$\hat{y}(n)$	output of the equaliser
J_{ft}	number tap of feed-forward filter

K_{bt}	number tap of feedback filter
$w(i)$	weight of feed-forward filter
$\tilde{w}(i)$	weight of feedback filter
$\check{d}$	decisions for previously detected symbols
$a(i)$	linear weight of feed-forward filter
$b(i, j)$	2nd weight of feedback filter
$c(i)$	weight of feedback filter
J	number tap of feed-forward filter
Q	number tap of feedback filter
$c(n)$	error factor
$d(n)$	desired symbol
T	transposition operation
$g(n)$	gain vector
$P(n)$	inverse correlation matrix
c'	extinction coefficient
$EV M_{RMS}$	the root-mean-squared average amplitude of the error vector
$S_r(n)$	normalized received nth symbol
$S_t(n)$	ideal value of symbol

Chapter 1

Introduction

1.1 Background

Oceans occupy two-thirds of the earth's territory, but despite this, they remain under-explored. Oceanic observation is of interest for a range of subject areas, including oil and gas exploration, monitoring pollution levels, and various military applications. Underwater communication technology is crucial for human exploitation of the ocean as many areas of interest are in deep, remote locations. The communication technologies that can be applied include wired and wireless systems. However, due to practical constraints in underwater exploration, it is difficult to build a wired communication system. In contrast, wireless communication is more flexible and suitable for remote underwater communication applications. Wireless communication using wireless carriers, i.e., radio frequency (RF) waves, acoustic waves, and optical waves, can transmit data in an unguided water environment [5]. However, each transmission technology has advantages and drawbacks that limit the practicality of underwater wireless communication. Table 1.1 provides a comparison of underwater acoustic communication (UAC), RF and underwater optical wireless communication (UOWC) for underwater applications [4].

- UAC can be traced back to 1490, Leonardo Da Vinci is credited with discovering the possibility to detect a distant ship by listening on a long tube submerged under the sea, and it quickly developed since the Second World War [8]. Now it is the primary technique for underwater wireless communication (UWC) as the long link range of up to several tens of kilometres. Whereas, the limited bandwidth (kHz) and large communication latency as the speed of sound (1500 m/s) limit the achievable data rate to the order for kbps [4, 5]. Although, many researchers have developed technological improvements such as channel estimation and advanced algorithms over the past few decades [9]. It still has various hurdles for effective communication due to the frequency-dependent attenuation, time-varying multi-path propagation and high latency. Meanwhile, it cannot be ignored that some artificial acoustic signals could have a high speed of harming marine life, thereby damaging ecosystems [10].

- RF technology is dominant for terrestrial wireless communication. It was initially considered for use in underwater environments because the speed of radio waves is much faster ($\approx 2 \times 10^5$ times) than that of sound travel through water [11]. Furthermore, RF signals can travel through several paths suffering from low attenuation such as air-water, and water-seabed [6]. And also, it has excellent resistance to dirty water and turbulence that happens in water [12]. However, due to the high water electrical conductivity at high frequency, RF in both very- and ultra-high frequency ranges are not easy to realise reliable communications larger than 10 m in the ocean [6] and RF antenna size is inversely related to the frequency that the frequency range for ultra-RF, the antenna size is very large. Whereas, the low-frequency ranges (3 Hz - 30 kHz) cannot support the high data rate [11] unless employing high consumption of power. In consequence, RF communication only can be limited to very short-range underwater applications.
- Considering the limitations of UAC and RF, using huge antennas or increasing transmission power seems to be an ineffective method. Hence, UOWC as an alternative option offers ultra-high transmission data rate (Gbps) with low latency at a distance of a few hundred meters that gains the significant interest of researchers [4, 5]. Although, UOWC also faces challenges: absorption and scattering, mainly due to the suspended particles and photon interactions in natural water; exact alignment requirement in the water between transmitters and receivers; reliable underwater devices which can adapt to the complex aquatic environment. It has the potential to provide complementary technology to acoustic and RF by providing high-speed, medium-distance links in future hybrid underwater communication networks. The specific application fields could be considered in the medium-distance links of port and coastal securities, ocean resources exploration, water pollution monitoring and submarine communication. For example, the underwater network is commonly employed by multiple network nodes and underwater vehicles in the water. If the nodes or vehicles of links are short distances, the communication scheme can use UOWC to replace UAC to achieve a much higher data rate, thus improving the efficiency of information exchange in hybrid underwater communication systems.

Table 1.1: *Comparison of Different Wireless Underwater Technologies [4–6]*

Parameters	Acoustic	RF	Optical (LED)
Attenuation	Distance and frequency-dependent (0.1 - 4 dB/km)	Frequency and conductivity dependent (3.5 - 5 dB/m)	0.39 dB/m (ocean) - 11dB/m (turbid)
Speed (m/s)	1500 m/s	$\approx 2.255 \times 10^8$ m/s	$\approx 2.255 \times 10^8$ m/s
Data rate	1.5 to 50 kbps (0.5 km) 0.6 to 3.0 kbps (28 - 120 km)	1 to 10 Mbps (1 - 2 m) 50 to 100 bps (200 m)	6.9 to 20 Gbps (1 - 2 m, [13, 14]) 400 Mbps (10 m, [15])
Distance	Kilometers	Few meters	Ten of meters
Bandwidth	Distance dependent : 100 km < 1 kHz ; 1 - 10 km $\approx$ 10 kHz ; < 100 m $\approx$ 100kHz	$\approx$ MHz	10 - 150 MHz
Transmission power	tens of Watts (typical value)	few mW to hundreds of Watts (distance dependent)	Few Watts
Performance parameters	Temperature, salinity and pressure	Water conductivity and permittivity	Absorption, scattering or turbidity, organic matter
Benefits	Mature technology; long distance	Relatively smooth transition to cross air/water boundaries; more tolerant to water turbulence and turbidity	High data transmission rate; immune to transmission latency
Limitations	Low data transmission rate; large latency	Short link range	Suffers from severe absorption and scattering; moderate link range

1.2 Motivation

Oceanic exploration requires reliable communication systems to meet modern communication requirements. As previously stated, UOWC offers the advantages of low cost, low latency, and high-speed communication links compared to acoustic and RF technologies, and higher speed over acoustic and RF.

UOWC has attracted interest from researchers in recent years and light emitting diodes (LEDs) have begun to be frequently used in UOWC research because of low cost and high stability characteristics. However, LED-based UOWC has the main limitation which is the narrow modulation bandwidth that comes from the commercial off-the-shelf LEDs. Hence, modulation techniques have attracted attention in recent years to improve spectral efficiency and enhance the system performance relatively. Since UOWC is implementing the conventional intensity modulation and direct detection (IM/DD) in water instead of in free space, the modulation techniques used in free space optical (FSO) communication can also be applied to UOWC systems. The spectrally efficient modulation schemes, namely pulse amplitude modulation (PAM), carrierless amplitude and phase modulation (CAP) and quadrature amplitude modulation (QAM) based orthogonal frequency division multiplexing (OFDM), will be used in this study to investigate techniques to overcome the bandwidth limitation associated with commercially available LED that will operate in a range of water conditions.

The optical signal is attenuated by the impact of absorption and scattering in water conditions leading to a poor bit-error-rate (BER) performance. In natural water, the turbidity is caused by matter and other coloured dissolved organic material (CDOM) which limits the propagation distance of the optical signal. It is also important to investigate how the effects of turbidity in the channel affect the UOWC system. This is important to give experimental results as reference data for practical applications considerably. It will be helpful for practical applications to aid the selection of the optimal modulation scheme for different water conditions.

1.3 Objectives

The aim of this thesis is to develop a greater understanding of the UOWC system for various modulation techniques presented in terms of link error performance and transmission rate in real water conditions. The results consist of theoretical and experimental studies. In order to achieve these aims, specific objectives are as follows:

- Using a UOWC channel model from literature, conduct a preliminary analytical study of the performance of the modulation techniques under test.
- Implement the modulation techniques under test in Matlab script for experimental evaluation.
- Implement equalisation techniques for modulation schemes in Matlab script.
- Experimentally characterise the UOWC channel in laboratory.
- Empirically compares the performance of the different modulation techniques in various underwater channel conditions.

1.4 Contributions and Publications

In this study, the main contribution is the comparison of different modulation techniques for LED-based UOWC system. System performance is evaluated in terms of the error performance of different modulation schemes under a range of underwater channel conditions. Throughout the study, some of the work contained in this thesis was disseminated in an IEEE-accredited conference publication:

- **Yu, M.**, Geldard, C. T., & Popoola, W. O. (2022, July). Comparison of CAP and OFDM Modulation for LED-based Underwater Optical Wireless Communications. In 2022 International Conference on Broadband Communications for Next Generation Networks and Multimedia Applications (CoBCom) (pp. 1-6). IEEE.
- **Yu, M.**, Geldard, C. T., & Popoola, W. O. (2022, December). Experimental Comparison of Modulation techniques for LED-based Underwater Optical Wireless Communications. In 2023 Wireless Communications and Networking Conference (WCNC) (accepted). IEEE.

1.5 Thesis Organization

This chapter provides the background and the motivations for underwater communication. The chapter also highlights the pros and cons of underwater wireless communication technologies, it illustrates that the UOWC is a vital part of the underwater wireless communication network, to make up for the shortfall of acoustic and RF. The rest of the thesis is structured as follows:

Chapter 2 presents the phenomenon of light propagation in water in terms of absorption and scattering. Inherent optical properties (IOPs), as well as the measurement used in this work, are described. The underwater channel modelling methods including Beer's law and the double-gamma function (DGF) denote the frequency response of coastal and harbour water conditions described. The channel bandwidth is obtained using the DGF, which shows the change in water channel conditions as turbulence increases. In addition, the impact of intersymbol interference (ISI) is calculated based on the DGF under the values of symbol duration. Then, both of them were used to evaluate the impact of the underwater environment on the error performance of UOWC.

Chapter 3 provides a background of the UOWC system. The light sources and optical detectors are the main components of the transmitter and receiver, respectively. The link configurations are discussed for UOWC and LEDs and LDs have been introduced in different characteristics that LED-based UOWC has the suitable features to apply in short distances of the turbid water that corresponds to real ocean. However, LED-based UOWC system has the primary challenge which is the limited modulation bandwidth. Thus, modulation schemes are described in terms of pulse amplitude modulation (PAM), carrierless amplitude and phase modulation (CAP), and quadrature amplitude modulation (QAM)-orthogonal frequency division multiplexing (OFDM). State of the art includes the recent work about LED-based UOWC in literature.

Chapter 4 describes equalisation techniques used in this work, including decision feedback equaliser (DFE), Volterra series-based decision feedback equaliser (VDFE) and zero forcing equaliser (ZFE). These are used to minimize the ISI caused by the LEDs transmitter and the effects of the UOWC channel. The equalisers commonly are classified as linear and nonlinear. In this work, a nonlinear equaliser, VDFE, is used to mitigate the impact of nonlinearity caused by LEDs that is more computational complexity than a linear equaliser, DFE. Both of these applied fast convergence algorithms, recursive least squares (RLS). Additionally, ZFE is also a linear equaliser, which inverts the frequency response of the channel. The principle is presented

and their merits are discussed.

Chapter 5 presents the experimental characterisation of the LED-based UOWC system. In this work, the UOWC channel is recreated in the laboratory using underwater channel emulator (UCE) which can emulate the real-world water channel. The transmitter employs a commercial blue LED and the result of received optical power as the drive current increases shows its nonlinearity. The modulation bandwidth in clear water, as well as the signal-to-noise-ratio (SNR) measured by error vector magnitude (EVM) in turbid water conditions, are presented, and these experimental results are obtained are used to inform the design of equalisation and modulation techniques later in the study.

Chapter 6 presents an empirical comparison of the performance of different modulation schemes in underwater channels. It begins with a comparison of CAP using DFE and VDFE in clear water, showing the performance of the equalisers and obtaining the optimal peak-to-peak voltage (V_{pp}). Then, the performance of CAP and QAM-OFDM is compared with various peak-to-peak voltages under different data rates. Furthermore, a comparison of PAM, CAP and QAM-OFDM in turbid water conditions shows the maximum data rate at the forward error correction (FEC) limit. Finally, the results are discussed with QAM-OFDM applying an improvement technology - bit and power loading (BPL).

Chapter 7 concludes all the works of this thesis. The future direction is given that targets the limitations of the presented work to develop the further potential application of LED-based UOWC.

Chapter 2

Underwater Optical Wireless Communications channel

In this chapter, the interaction of light and water in the UOWC channel is discussed. The issue of absorption and scattering is the main factor that leads to power loss and distortion of the transmitted signal in the UOWC channel.

2.1 The UOWC Channel Factors

2.1.1 Absorption

Light absorption is caused by water itself as well as suspended materials within the water. The absorption coefficient for pure water was determined by Smith and Baker in [16] covering the waveforms range (200 – 800 nm). But even if the absorption by the water itself is taken as known, the determination of the absorption coefficient for natural waters still is a difficult task. It is because the absorption measurement needs to carefully consider the scattering effect as it is hard to separate from scattering and more absorption due to the suspended materials in the water. Suspended materials include CDOM and phytoplankton. CDOM absorbs little in the red but more in blue and ultraviolet wavelengths, while phytoplankton cells are strong absorbers of the blue and red, with little green, due to the chlorophyll in their composition [17]. In [1], it was found that a transmission window (blue and green spectrum) in 1963 with the smallest attenuation coefficient for light waves in the wavelength range of 400 nm - 500 nm in seawater. This window provides the optimal wavelength for UOWC to minimize the aquatic optical attenuation, and is illustrated in Figure 2.1.

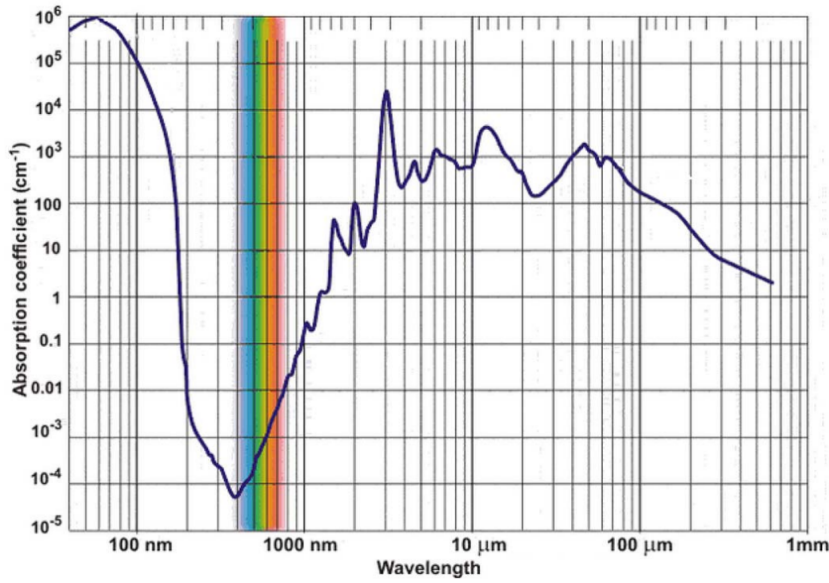


Figure 2.1: *The measured attenuation coefficient over a range of wavelengths in clean water [1].*

2.1.2 Scattering

Scattering occurs when a photon interacts with water molecules, particulate matter, and dissolved substances but rather than being absorbed, its direction is altered and it continues propagating. The power dispersion raised from scattering is dependent on the angle, ψ , of the deviation from the original direction and solid angle, φ , includes all directions within the annular ring, as shown in Figure 2.2. In natural water, organic, and inorganic particles, the special case of large-scale turbulence all can cause small-angle scattering. Photon and water molecules, and salt ions in seawater induced small-scale scattering that determines the minimum values for the scattering properties [1]. The author in [18] compared the different light sources in clear water with a single turbulence-induced scattering boundary. The result shows turbulence has little effect on the light from an LED consisting of a larger number of different wavelengths enabling the mitigation of the effects of turbulence. In this thesis, we used the LED to investigate the UOWC system so that turbulence-induced scattering will not be considered in the experiment.

2.2 Light Propagation in Water

The inherent optical properties (IOPs) describe the optical properties of natural waters in terms of radiative transfer theory [2]. When considering light propagation through a differential volume element of water of width Δr , some photons will be absorbed or scattered within the medium. Absorption occurs when the photons are absorbed within the medium, leading to a reduction in the received power. Whereas, scattering occurs when a portion of light leaving the volume does not retain the same propagation direction, while it will be distributed in other directions. This is illustrated in Figure 2.2 taken from reference [2].

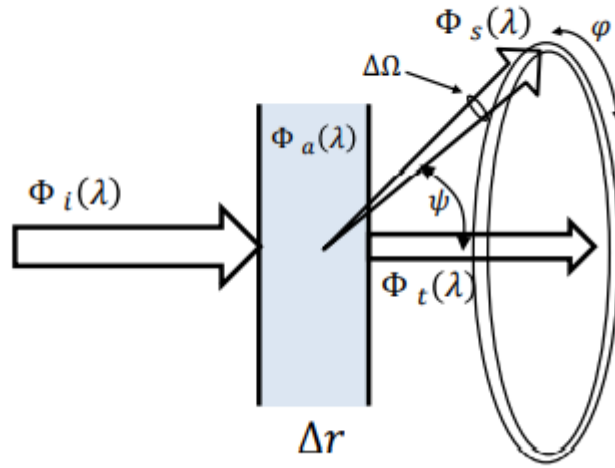


Figure 2.2: Geometry of the inherent optical properties of water [2]

2.2.1 The Inherent Optical Properties

As illustrated in Figure 2.2, considering incident light in a differential volume of water defined as a spectral radiant power of $\Phi_i(\lambda)$, then $\Phi_a(\lambda)$ is the absorbed power, $\Phi_s(\lambda)$ is the total scattered power within the annular ring φ in all possible direction angle ψ by the solid angle $\Delta\Omega$, and $\Phi_t(\lambda)$ is the portion of the light that passes through the channel without being affected by absorption or scattering. Due to energy conservation, the total incident power is equal to the sum of all power absorbed, scattered, or transmitted through the channel, as in [2]:

$$\Phi_i(\lambda) = \Phi_a(\lambda) + \Phi_s(\lambda) + \Phi_t(\lambda) \quad (2.1)$$

We can define the absorptance $A(\lambda)$ as [2]:

$$A(\lambda) = \frac{\Phi_a(\lambda)}{\Phi_i(\lambda)} \quad (2.2)$$

Likewise, the scatterance $B(\lambda)$ as [2]:

$$B(\lambda) = \frac{\Phi_s(\lambda)}{\Phi_i(\lambda)} \quad (2.3)$$

Commonly, absorption coefficient $a(\lambda)$ and scattering coefficient $b(\lambda)$ are employed in UOWC to represent the IOPs. They are the absorptance and scatterance per unit distance Δr [2]:

$$a(\lambda) = \lim_{\Delta r \rightarrow 0} \frac{\Delta A(\lambda)}{\Delta r} = \frac{dA(\lambda)}{dr} \quad (2.4)$$

$$b(\lambda) = \lim_{\Delta r \rightarrow 0} \frac{\Delta B(\lambda)}{\Delta r} = \frac{dB(\lambda)}{dr} \quad (2.5)$$

Then, the sum of both of these coefficients is defined as the attenuation coefficient, $c(\lambda)$, given in units of m^{-1} :

$$c(\lambda) = a(\lambda) + b(\lambda) \quad (2.6)$$

Similarly, the attenuation coefficient, $c(\lambda)$, as

$$c(\lambda) = \frac{dC(\lambda)}{dr} \quad (2.7)$$

The $a(\lambda)$, $b(\lambda)$ and $c(\lambda)$ were measured in real water conditions in [19], which covers the wavelength range (300 - 700 nm) and it classified $c(\lambda)$ into variant levels of water types. These case studies provide a useful reference for researchers when recreating realistic water conditions in simulation or laboratory-based experiments. Additionally, values of $a(\lambda)$, $b(\lambda)$, and $c(\lambda)$ were estimated for $\lambda = 475$ nm (the wavelength of LED used in this work) that provided a real-world water criterion for comparing laboratory experiments as shown in Table 2.1.

Table 2.1: Jerlov water types for 475 nm

Water types	$a(\lambda)$	$b(\lambda)$	$c(\lambda)$
Jerlov I	0.019	0.00306	0.02206
Jerlov IA	0.0216	0.00536	0.02696
Jerlov IB	0.0225	0.0635	0.086
Jerlov II	0.0228	0.459	0.4818
Jerlov IC	0.077	0.469	0.546
Jerlov III	0.0335	1.26	1.2935
Jerlov 3C	0.105	1.36	1.465
Jerlov 5C	0.204	1.71	1.914
Jerlov 7C	0.388	3.01	3.398
Jerlov 9C	0.709	4.01	4.719

2.2.2 Measuring IOPs

The definitions of the absorption and scattering coefficients have been described in terms of an infinitesimally thin slab of water in (2.1)- (2.7). The conceptual definitions of IOPs must be reformulated in order to be useful in practical experiments [17].

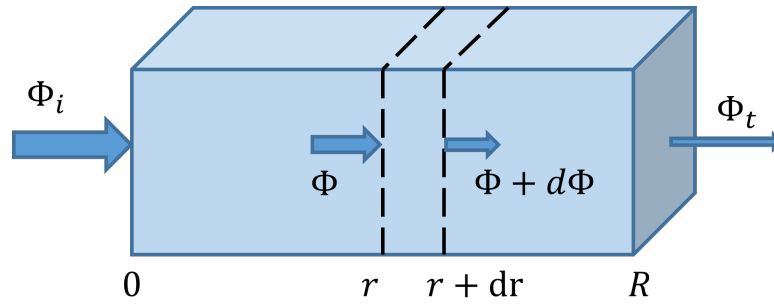
**Figure 2.3:** Geometry of measurement of beam attenuation c

Figure 2.3 shows a finitely thick slab of water with an incident power $\Phi_i(\lambda)$ and transmitted power $\Phi_t(\lambda)$ for measurement of beam attenuation $c(\lambda)$. Within the slab, the magnitude of the power has, $\Phi(\lambda)$, when it is passing through a thickness r of the medium. Therefore, the Φ will change from $\Phi(\lambda)$ to $\Phi(\lambda) + d\Phi(\lambda)$ via a thickness r to $r + dr$. Equation (2.7) can be rewritten as:

$$c(\lambda) = \frac{dC(\lambda)}{dr} = \frac{-\frac{d\Phi(\lambda)}{\Phi}}{dr(\lambda)} \quad (2.8)$$

or,

$$c(\lambda)dr = \frac{d\Phi}{\Phi} \quad (2.9)$$

We assume the medium is uniform, c is independent of r , (2.9) can be integrated from $r = 0$ to $r = R$, which corresponds to the incident power Φ_i and received power Φ_t . Thus, the c gives as:

$$\int_0^R c(\lambda)dr = c(\lambda)R = - \int_{\Phi_i(\lambda)}^{\Phi_t(\lambda)} \frac{d\Phi(\lambda)}{\Phi(\lambda)} = - \ln\left(\frac{\Phi_t(\lambda)}{\Phi_i(\lambda)}\right), \quad (2.10)$$

$$c(\lambda) = -\frac{1}{R} \ln \frac{\Phi_t(\lambda)}{\Phi_i(\lambda)}. \quad (2.11)$$

This equation denotes the beam attenuation coefficient in terms of the measurable incident and transmitted powers in the finite thickness of the slab.

2.3 UOWC Channel Model

Modelling the effects of IOPs is necessary for analysing the problems in many real-world applications of the UOWC system. Not only are the measurements of the volume scattering functions extremely difficult, but also require expensive, time-consuming, and dangerous sea voyages to measure actual ocean environments. Many different types of analytical schemes have been used over the years. The Henyey-Greenstein function was proposed by Toubanc in [20] based on interstellar dust scattering. Later, the Fournier-Forand function in [21] has been used with good agreement to measure the actual water based on the anomalous diffraction approximation of Van de Hulst [22]. Mobley et al. in [23] re-parameterized the FF function based on the backscattering fraction. Beer's law is used by Smart [24] and Giles [25] and Bankman to evaluate the performance of the UOWC system in a range of water types and distance links. Freda and Piskozub in [26] gave an additional set of parameterizations that improved the fit of the experimental data and natural waters compared to Mobley's result. Here, Beer's law and double gamma function are used to present the characteristics of the underwater channel model in this study.

2.3.1 Beer' Law

Beer's law is the simplest method to model the UOWC channel by describing the light propagation loss in the water without considering the impacts of environmental variability (such as refractive index). The expression for Beer's law channel loss as a function of wavelength and distance is given [5]:

$$I_r = I_t e^{-c(\lambda)L} \quad (2.12)$$

where I_r is the final optical power at the receiver, I_t is the initial optical power at the transmitter, L is the light transmission distance in the water, and $c(\lambda)$ is the attenuation coefficient for specific water types.

Beer's law is assuming the system alignment is perfect and all scattered photons of the path are lost. However, the pronounced scattering increases when the light propagates to a larger distance in the physical link range. There are some scattered photons maybe arrive at the receiver so Beer' law underestimated the optical power received in the actual water environment, especially in the scattering dominant condition. Thus, it is widely used to model the aquatic optical attenuation in line-of-sight for simplicity.

2.3.2 Double-Gamma Function

Initially, the double-gamma function (DGF) was used in [27] for modelling the impulse response of photons propagating across clouds. Inspired by this, in [28], Tang et al. applied DGF to model the impulse response in the direct line-of-sight (LOS) laser-based UOWC links. Here, the DGF was fitted to the impulse response obtained through a photon-tracking Monte-Carlo (MC) simulation based on radiative transfer theory. This technique has been commonly used for UOWC channel modelling, including in references [3, 28, 29]. As shown in Equation (2.13), the DGF is a mathematical expression in the time domain [28], it has two independent Gamma functions to present the direct LOS and the Non-LOS constituents of the channel.

$$h(t) = C_1 t \exp(-C_2 t) + C_3 t \exp(-C_4 t) \quad (2.13)$$

Here, the left term represents the direct LOS, the right term represents the Non-LOS and C_i , $i = [1, 2, 3, 4]$ are parameters obtained by comparing with MC numerical simulation. Values of C_i for the channel conditions used in this work are shown in Table. 2.2. They are taken from

reference [3] and represent 15 m and 30 m harbour and coastal water channels, respectively, for laser-based UOWC in a range of turbulence-induced scattering conditions. Although this study considers LED-based UOWC, it is still useful to consider the hostile channel conditions experienced by a laser when examining link performance in an extreme scenario.

Table 2.2: Fit parameters for DGF from MC simulation [3].

$b_t(m^{-1})$	C_1	C_2	C_3	C_4
30m, Coastal water				
0	2×10^6	1.15×10^{11}	4072	1.2×10^{10}
0.05	5.5×10^5	1×10^{11}	2544	1×10^{10}
0.1	1.86×10^5	9×10^{10}	2953	1.2×10^{10}
0.2	1.2×10^4	3×10^{10}	435	6×10^9
15m, Harbour water				
0	600	3.8×10^9	28.49	9×10^8
0.5	160	3.0×10^9	23.69	9×10^8
1	60	2.4×10^9	12.51	7.5×10^8
2	8.9	1.2×10^9	2.4	4.5×10^8

Impulse responses based on the DGF are presented in Figure 2.4. The harbour link has a channel gain of 10^{-8} compared to 10^{-6} for coastal, which means the attenuation caused by the harbour water is stronger than that of the coastal water despite being half the distance. And as the value of the two types of seawater turbulence reflected in the intensity of channel gain, this can be explained by turbulence-induced scattering resulting in the intensity reduction.

2.3.3 Channel bandwidth

The channel bandwidth can be calculated based on the DGF of both water channels' impulse response [28]. The frequency response of (2.13) is obtained by taking a Fourier transform:

$$H(2\pi f) = \frac{C_1}{(j2\pi f + C_2)^2} e^{j2\pi f t_0} + \frac{C_3}{(j2\pi f + C_4)^2} e^{j2\pi f t_0} \quad (2.14)$$

where f is the frequency in the unit of Hz, j is the imaginary unit, $t_0 = L/v$ is the light propagation time which is the ratio of link distance L over light speed v in water ($2.25 \times 10^{-8} \text{ms}^{-1}$).

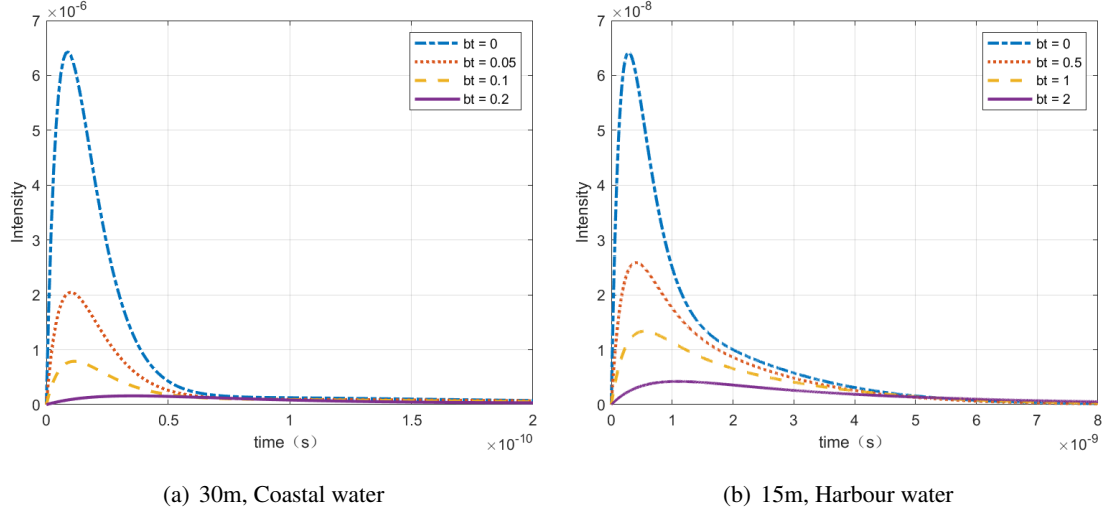


Figure 2.4: Impulse response of water channel model with variant turbulence by DGF [3].

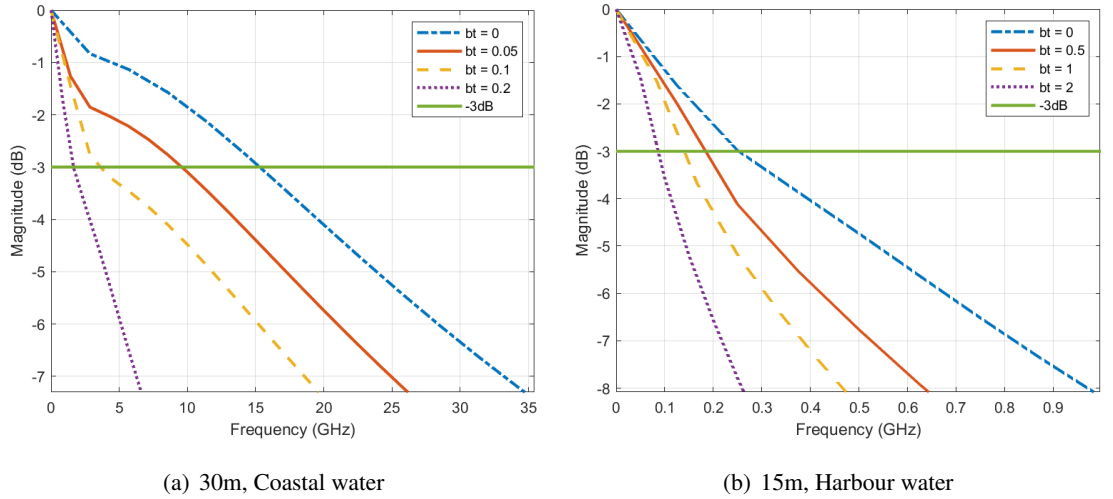


Figure 2.5: The channel bandwidth with variant turbulence values

The channel bandwidth is illustrated in Figure 2.5 and the values are given in Table. 2.3. As the turbulence-induced scattering increases, channel bandwidth decreases in both coastal and harbour water conditions. Compared to harbour water, coastal water has wider bandwidth even for a longer transmission link.

Table 2.3: *The channel bandwidth in coastal and harbour water with variant turbulence values*

30m, Coastal water		15m, Harbour water	
$b_t(m^{-1})$	-3dB channel bandwidth (GHz)	$b_t(m^{-1})$	-3dB channel bandwidth (GHz)
0	15	0	0.25
0.05	9.5	0.5	0.18
0.1	3.5	1	0.15
0.2	1.6	2	0.08

2.3.4 Intersymbol Interference Impact

The DGF can be used to estimate by a distortion factor (α) that evaluates the impact caused by ISI in the UOWC. This represents the ratio of signal intensity that decays through a dispersive channel. It means that the α equals a ratio of signal power loss depending upon the symbol duration to the total signal power [30] and it can be simplified by the first moment expressions.

$$\alpha = \frac{\int_T^\infty h^2(t)dt}{\int_0^\infty h^2(t)dt} \approx \frac{\int_T^\infty h(t)dt}{\int_0^\infty h(t)dt} \quad (2.15)$$

Where $h(t)$ is the channel impulse response, T is the symbol duration that depends on the sampling frequency. The high symbol rate causes the narrow symbol duration, which leads to α increases. According to the (2.15), the α can be plotted as symbol duration increases, as shown in Figure 2.6.

Also, the α can be calculated by symbol rate ($R_s = 1/T$). For example, if the symbol rate at 4.2 Gsym/s in coastal water and 200 Msym/s in harbour water and, both without turbulence, $\alpha = 0.0229$ and $\alpha = 0.0253$, respectively. The similar α between coastal and harbour water despite a large difference in symbol rates highlights the difference in bandwidth for the two channels.

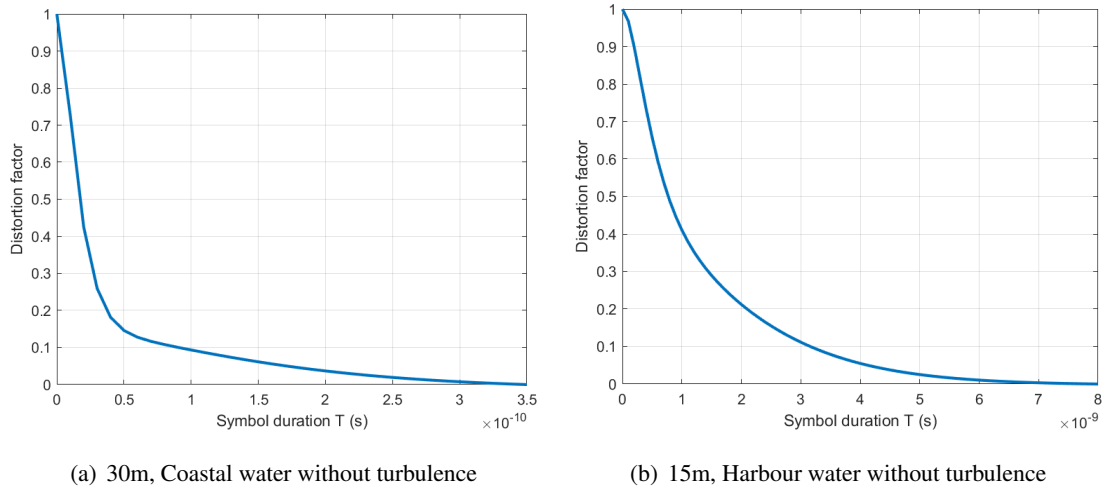


Figure 2.6: The distortion factor vs symbol duration

In a LOS channel with no ISI, the SNR is commonly calculated as expressed [7]:

$$SNR = \frac{\kappa^2 R^2 H^2(0) P_t^2}{\sigma_n^2} \quad (2.16)$$

where σ_n^2 is sum of thermal noise and shot noise, P_t is average transmit optical power, κ is the an electrical-to-optical conversion factor of LED, R is the responsivity of a photodetector, $H(0) = \int_{-\infty}^{\infty} h(t)dt$ is the Channel direct current Gain.

This can be adapted for an ISI channel using α for accounting for power lost from the target symbol period that leaks into the interfering symbol period as interference. The signal-to-interference and noise ratio (SNR_{ISI}) can be expressed as [30]:

$$SNR_{ISI} = \frac{\kappa^2 R^2 H^2(0)(1 - \alpha) P_t^2}{\sigma_n^2 + \kappa^2 R^2 H^2(0) \alpha P_t^2} \quad (2.17)$$

If PAM or QAM signal via a channel with the ISI, such as $\alpha = 0.0229, 0.055$ and parameters in [30] ($\kappa = 14.15mW/A, R = 0.28A/W, H(0) = 1, P_t = 1W$), the theoretical result of BER can be calculated based on the received SNR_{ISI} for PAM and QAM as in (2.18) and (2.19), respectively [31, 32]. The BER is targeted at the forward error correction (FEC) limit (3.8×10^{-3}) for the error within feasible communication.

$$BER_{PAM} = \frac{2(1 - \frac{1}{M})}{\log_2 M} \times Q\left(\sqrt{\frac{6(SNR_{ISI})}{M^2 - 1}}\right) \quad (2.18)$$

$$BER_{QAM} = \frac{4(1 - \frac{1}{\sqrt{M}})}{\log_2 M} \times Q\left(\sqrt{\frac{3(SNR_{ISI})}{M-1}}\right) - \frac{4(1 - \frac{1}{\sqrt{M}})^2}{\log_2 M} \times Q^2\left(\sqrt{\frac{3(SNR_{ISI})}{M-1}}\right) \quad (2.19)$$

where M is the modulation order, $Q(\cdot)$ is the Gaussian Q-function.

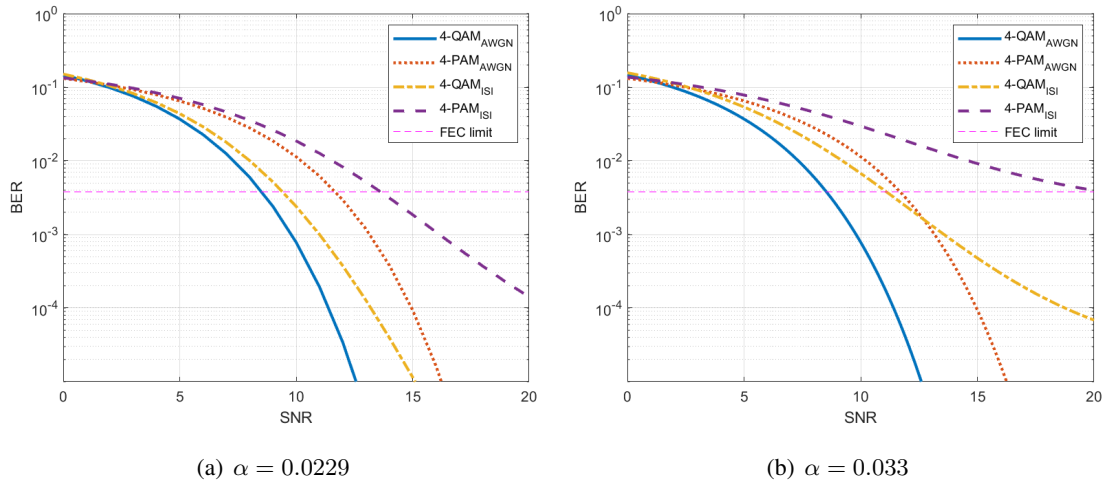


Figure 2.7: Comparison BER of 4-PAM and 4-QAM with ISI

Figure 2.7 shows the analytical BER against normalised SNR for PAM and QAM with $M = 4$ in two different ISI channels with the additive white Gaussian noise (AWGN) channel for reference. 4-QAM only with AWGN reaches the FEC limit at around 8.5 dB, while the SNR requirement is increasing to around 9.5 dB when affected by ISI distortion. In contrast, 4-PAM requires a higher SNR compared to 4-QAM to reach the FEC limit of around 11.6 dB and it has the impact of ISI then increasing to around 13.6 dB. The growth gap between QAM and PAM shows that QAM has better resilience to ISI than PAM. If the α gradually increases, 4-PAM will not be satisfying the transmission requirement at 13.6 dB as shown in Figure 2.7b, requiring a further increase to 20 dB to achieve the FEC limit. Thus, the impact of ISI acts to limit the error performance data transmission at a certain symbol rate. The signal affected by severe ISI even has a negative impact on achieving reliable communication.

2.4 Summary

In this chapter, the UOWC channel was described in terms of IOPs, this channel was then used for a preliminary evaluation of the impact of ISI. Commonly, scattering is a key component of the UOWC channel due to the those dissolved particles, substances and turbulence than the scattering in natural water. The attenuation coefficient measurement depends on the change of power magnitude passing through the distance of the link. Using the commonly used DGF UOWC channel model, it was shown that the bandwidth is gradually narrowed and the impact of ISI becomes serves as the scattering increases, respectively. Finally, using the DGF, the ISI distortion factor was calculated and subsequently used to evaluate the BER of PAM and QAM transmission in the ISI channel. It was shown that ISI has a significant impact on data transmission and there is an SNR penalty due to ISI that must be accounted for in the link margin if a target BER performance is to be maintained.

Chapter 3

Underwater Optical Wireless Communication System

3.1 Background

Underwater optical wireless communication (UOWC) has the advantages of comparatively small, low-energy consuming, and low-cost optical transceivers in underwater wireless communication (UWC). Notably, the high-speed data rate makes it a promising candidate for real-time applications such as underwater video transmission. However, some key challenges need to be considered before implementation.

- Absorption and scattering are inevitable attenuation of the transmitted optical power even if carefully using the lowest attenuation wavelength region (blue to green) in the water.
- Link misalignment between the optical transceivers frequently happens due to the turbulence at relatively shallow depths.
- The pressure, temperature, flow, and salinity of the aquatic environment greatly impact the performance and lifetime of UOWC devices [33].

Thus, designing UOWC systems requires careful selection of reliable optical devices and channel estimation.

3.2 Optical sources

For UOWC, light sources need to be selected to adapt to the underwater environment. Commonly, light emitting diodes (LEDs) and laser diodes (LDs) are used in UOWC including references [13, 34–36] and [37–40], respectively. Both LEDs and LDs are semiconductor p-n junction devices and offer several advantages (i.e., small size, reliability, etc). Their characteristics are presented in Table 3.1.

Table 3.1: Comparison of an LED and a semiconductor LD [7].

Characteristics	LED	LD
Optical output	Low power	High power
Optical spectral width	25–100 nm	0.01–5 nm
Modulation bandwidth	Tens of kHz to hundreds of MHz	Tens of kHz to tens of GHz
Electrical to optical conversion Efficiency	10–20%	30–70%
Eye safety	Considered eye safe	Must be rendered eye safe
Directionality	Beam is broader and spreading	Beam is directional and is highly collimated
Reliability	High	Moderate
Coherence	No	Yes
Temperature dependence	Little temperature dependence	Very temperature dependent
Drive and control circuitry	Simple to use and control	Threshold and temperature compensation circuitry
Cost	Low	Moderate to high

3.2.1 The Laser Diode

Laser stands for light amplification by stimulated emission of radiation [41]. The luminescence mechanism of the conventional light source is spontaneous radiation, there is no external effect on the process, the radiation of each atom is spontaneous and independent, and the emission direction and initial phase of each photon are different. Therefore, atoms are in different excited states, and different frequencies so that the spontaneously emitted light is generally not monochromatic, and it is not coherent light [42]. However, the laser is coherent light, and its luminescence process is stimulated radiation, if an atom in the excited state interacts with a photon produced by spontaneous radiation, the atom may be stimulated by the photon from the high energy level to the low energy level and radiate a second photon. The photon produced by stimulated radiation has the same characteristics as the first photon, so their frequency, phase, vibration direction and propagation direction are the same, resulting in coherent light. In addition, it is also necessary to achieve the condition called population inversion that which aims to reverse the distribution of most atoms at the low energy level and a few atoms at the high energy level of the material to produce light amplification. The population inversion is supported by the high drive currents and the occurring optical feedback effect maintains the lasing action when the drive forward current keeps above the threshold level [7].

LDs provide high power, narrow spectral width, high temporal coherence and high spatial coherence but the light beam is narrow and sensitive to temperature. In UOWC, due to the narrow spectral width and high output power, LDs enable a high-speed longer distance transmission than LEDs. However, it also has high requirements for alignment and it has low resistance to turbulence happened in underwater [7].

3.2.2 The Light-Emitting Diode

LEDs and LDs are similar in materials and heterogeneous structures. The main structural difference between the two is that the LED does not have an optical resonator so that cannot form a laser. The emission of LED originates from spontaneous radiation, emitting fluorescence, which is incoherent light. In order to obtain high radiation, LEDs generally use a dual heterogeneous structure [7]. According to the light-emitting surface parallel or perpendicular to the p-n junction, it is divided into planar LEDs and edge LEDs. Compared with LDs, due to the differences in the luminescence mechanism and structure, there are obvious differences in their main performance. For instance, there is no threshold for LEDs, under certain drive conditions there is a linear relationship between output optical power and the injection current. For UOWC, it is desirable for the LED transmitter to operate within this linear region. When the injection current is large, the luminous efficiency decreases due to the heat generation of the p-n junction, and saturation occurs - making the relationship between drive current and optical power non-linear [7]. Since LEDs output spontaneous radiation and do not have optical resonators, the output spectrum is much wider than that of semiconductor lasers. Additionally, the output optical power of the LED does not change much with temperature, temperature control is not required in normal operation. Although low optical output limited the transmission distance it can be solved by a LED array [14]. And the wide divergence is suitable for diffused LOS links underwater. Furthermore, the advantages of LEDs make them suitable for use in remote sensing applications, including long life, high reliability, simple modulation circuit, high tolerance of turbulence and low cost, so it is selected in this work.

3.3 Link Configuration of UOWC

The link configuration of UOWC can be classified into two categories: Direct LOS configuration and Non-LOS configuration [4,5]:

- Direct LOS configuration is the most commonly used link in UOWC. Namely, there is a point-to-point connection with no obstructions between the transmitter and receiver. It requires a perfect alignment as well as employs a highly coherent light source with a narrow divergence angle such as LDs. However, precise alignment is easily met in an experimental environment but it is difficult to achieve in a real underwater channel. Especially for the application of transmitter and receiver are non-stationary nodes and working in turbulent water environments.
- Non-LOS configuration concludes reflective and diffuse conditions. A reflective link occurs when the transmitter emits a light beam with an angle of incidence larger than the critical angle towards the ocean-air interface. The light beam will totally reflect back to the ocean. The receiver needs to towards the interface corresponding to the reflective angle. The challenge of the link is the randomly fluctuating sea surface would reflect the light in a random direction even back to the transmitter resulting in signal dispersion. While diffuse link occurs when employing diffused light sources such as LEDs with large divergence angles to transmit signal from one node to multiple nodes. The diffused light commonly is applied at short distances and has lower data rates because the long distance depends on the area of interaction with water that suffers from severe attenuation. Non-LOS link common in turbid water does not require strict alignment so the high-power LED or LED array is more suitable.

3.4 Detectors

At the receiver, two types of photodiodes are widely used in UOWC experiments: p-type intrinsic n-type diode (PIN) photodiode and avalanche photodiode (APD) [43].

The major difference between these two devices lies in the noise performance. For PIN photodiodes, the dominant noise is thermal noise, while for APD, the performance is mainly limited by shot noise [44]. In the non-LOS links of turbid water conditions, more sensitive detectors are capable of capturing the light after severe attenuation. In general, the sensitivity of the APD

photodiode is higher than that of the PIN photodiode. Additionally, APD can provide high current gain, and it can be implemented in longer UOWC links (> 10 m), but at the expense of high power requirements. However, PIN photodiodes are commonly cheaper than APD, instead of opting for high gain APD, choosing high bandwidth PIN can be a better option within a short-distance experiment. In this study, a reverse-biased PIN photodiode is used, mated to a fixed gain trans-impedance amplifier, and packaged in a rugged housing.

3.5 Modulation Schemes

LED-based UOWC has the main drawback which is the limited bandwidth of commercially available LEDs. In order to overcome the bandwidth limitations, modulation techniques employed in LED-based UOWC should be spectrally efficient when a high data rate is targeted. In UOWC, the signal is transmitted using IM/DD. Therefore, multilevel modulation schemes use a higher modulation order, M , to increase the spectral efficiency and overcome the bandwidth limitation [45].

3.5.1 Pulse Amplitude Modulation

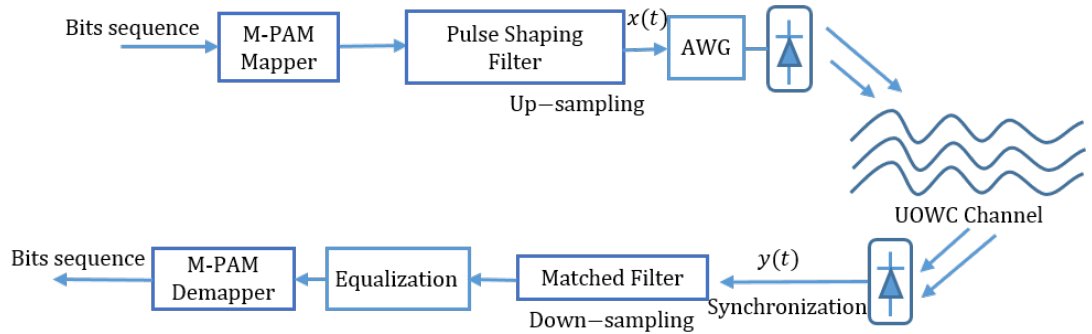


Figure 3.1: The block diagram of PAM transceiver

The simplest form of IM/DD modulation is to encode data on the amplitude of the optical carrier signal, it is pulse amplitude modulation (PAM) [7]. The PAM techniques have been used in UOWC literature, including [13, 15, 35, 46]. Here, the modulation order, M , can be increased by increasing the number of amplitude levels in the signal. The spectral efficiency of PAM can be further improved by employing a pulse shaping filter, such as the square-root raised-cosine (SRRC) filter, to make better use of the available bandwidth [47].

Figure 3.1 shows a block diagram for PAM transceiver. The random bits are modulated by a PAM modulator in M level. The mapped symbols s_k are up-sampled by the SRRC filter $g_{SRRC}(t)$ [48]:

$$S_{PAM}(t) = \sum_{k=-\infty}^{+\infty} s_k g_{SRRC}(t - kT) \quad (3.1)$$

where T is the symbol duration, k is number of symbol.

The bandwidth of PAM, B_{PAM} , is controlled by the maximum frequency of the $g_{SRRC}(t)$ [48]:

$$B_{PAM} = \frac{(1 + \beta)}{2T} = \frac{(1 + \beta)D_b}{2m_{PAM}} \quad (3.2)$$

where β is the roll-off factor value, D_b is the bit rate and m_{PAM} is $\log_2 M$ denoting the bits per symbol. At the receiver, there is a matched filter for the received signal and then down-sampled before the equalisation. The equaliser used in PAM will be introduced in the following chapters. The demodulation process is integrated into equalisation.

3.5.2 Quadrature Amplitude Modulation

An alternative to PAM is the two-dimensional signalling of quadrature amplitude modulation (QAM) [7]. QAM mapper split incoming bit stream into chunks of M bits. It uses $M/2$ bits to define a PAM sequence and uses the remaining $M/2$ bits to define an independent PAM sequence. It means QAM transmits two PAM signals using carriers of the same frequency but in phase and quadrature. For example, Figure 3.2 shows the 4-QAM constellation. QAM adds the extra dimension of phase, but cannot be directly implemented in OWC as it has imaginary components. Therefore, techniques including carrierless amplitude and phase modulation (CAP) and orthogonal frequency division multiplexing modulation (OFDM), are commonly used in OWC in order to implement QAM, these are compared in this study.

3.5.2.1 Carrierless Amplitude and Phase Modulation

The originally CAP was proposed by Bell Labs to overcome the limitation for high-speed communication wires in 1970s [49,50]. Nowadays, it is commonly employed to provide high spectral efficiency with low complexity and costs in the UOWC system [51–53]. CAP uses a pair of orthogonal carriers, in-phase and quadrature-phase (I/Q) components, generated by finite digital impulse response filters, SRRC filters, to implement QAM [48]. Its principle of operation

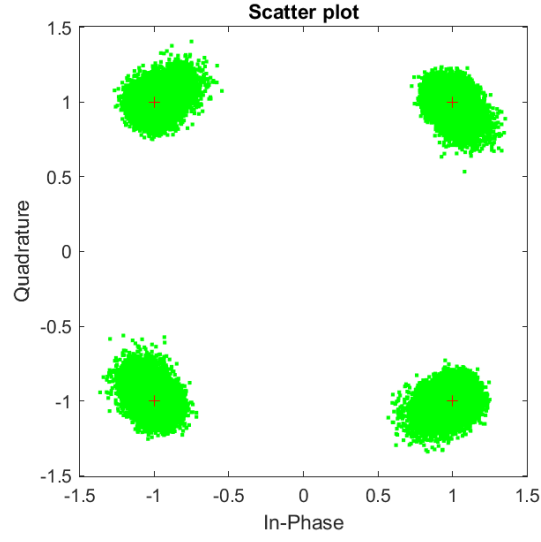


Figure 3.2: 4-QAM signal constellation

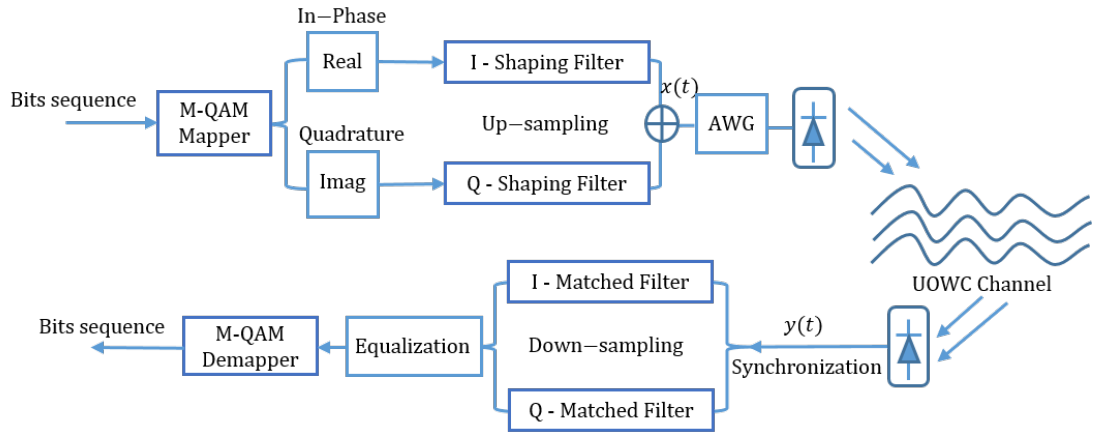


Figure 3.3: The block diagram of CAP transceiver

is similar to that of QAM but does not require the use of local oscillators (LOs), RF mixers and phased locked loops which add complexity to the electronic circuits [54]. This gives the CAP transceiver design and implementation low complexity and low cost. However, the necessity of a channel equaliser in processing the received CAP data increases the complexity of CAP transmission. The spectral efficiency of CAP may be increased by using multi-level QAM, thus increasing the number of bits per symbol [47]. The two orthogonal pulse shaping functions are typically based on the SRRC function $g(t)$ as the combination of the two functions used at the transmitter and the receiver results in a raised cosine filter response which satisfies the Nyquist criterion of zero ISI at the sampling points $t = nT, n \in \mathbb{Z}$.

$$g_{SRRC}(t) = \frac{\sin[\pi(t/T)(1 - \beta)] + 4\beta(t/T)\cos[\pi(t/T)(1 + \beta)]}{\pi(t/T)[1 - (4\beta(t/T))^2]} \quad (3.3)$$

where β is the roll-off factor of the SRRC function which takes a value between 0 and 1, T is the symbol period. Previous works in literature are widely used $\beta = 0.15$ to provide good performance [55–58]. This value of β is therefore used throughout this study. The orthogonal pulse shaping functions for the I and Q components are formed by multiplying the SRRC function with a cosine and a sine wave with center frequency f_c , given by $f_c = (1 + \beta)/2T$ which must be equal or greater than the maximum frequency of $g_{SRRC}(t)$ to avoid any aliasing [47], resulting in the two pulse shaping filters, h_I and h_Q , form a Hilbert transform pair having a spectrum with the same amplitude but with a 90-degree phase difference which makes them orthogonal [59]. Figure 3.4 shows the waveforms of SRRC filter, I and Q components when the β equal 0.15.

$$h_I(t) = g_{SRRC}(t) \cos(2\pi f_c t), \quad (3.4)$$

and

$$h_Q(t) = g_{SRRC}(t) \sin(2\pi f_c t) \quad (3.5)$$

Then, CAP signal can be defined as:

$$S_{CAP}(t) = \sum_{k=-\infty}^{+\infty} a_k h_I(t - kT) - b_k h_Q(t - kT) \quad (3.6)$$

where a_k and b_k are the real and imaginary parts of the QAM symbol.

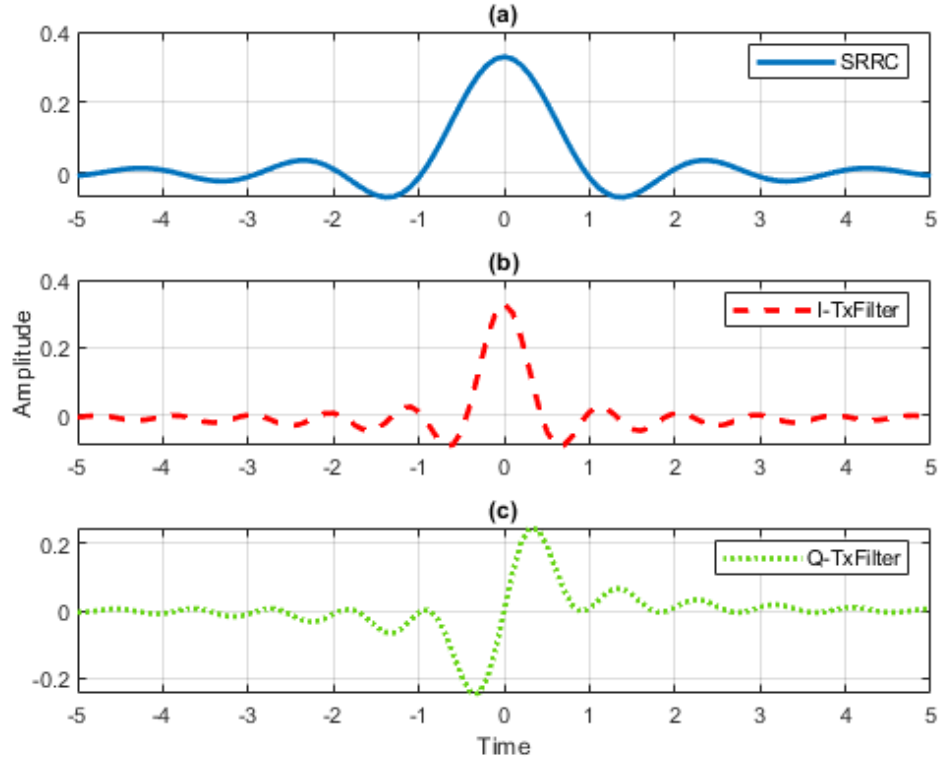


Figure 3.4: The waveform for (a) SRRC, (b) I component, (c) Q component

Similarly, the bandwidth of CAP, B_{CAP} , is [48]:

$$B_{CAP} = \frac{(1 + \beta)}{T} = \frac{(1 + \beta)D_b}{m_{CAP}} \quad (3.7)$$

where m_{CAP} is the bits per CAP symbol.

Comparing equation 3.2 and 3.7, the spectral efficiency, η , of PAM and CAP can be expressed by the ratio of the bit rate and the total occupied bandwidth B :

$$\eta = \frac{D_b}{B} = \frac{2m_{PAM}}{(1 + \beta)} = \frac{m_{CAP}}{(1 + \beta)} \quad (3.8)$$

so when keeping the spectral efficiency of PAM and CAP to the same, $m_{CAP} = 2m_{PAM}$, the bits per symbol for CAP should be twice that of PAM in this study, and it is the same criterion to QAM-OFDM.

Figure 3.3 shows a block diagram describing data transmission with the CAP modulation sys-

tem. At the transmitter, a stream of bits is mapped to the M -QAM constellation to complex symbols. The real part modulates the in-phase pulse shaping filter whereas the imaginary part modulates the quadrature pulse shaping filter. The I and Q components are up-sampled and then combined together to form the CAP signal that modulates the LED. The prepared signal is then transmitted via the channel in this work of underwater link. At the receiver side, the signal is detected by the photodetector and recovered by the photodiode using direct detection and is synchronized to correct any timing errors caused by the channel and filtering operation. Next, the received electrical signal is fed into two matched filters that have time-inverse pulse-shaping to separate back into I and Q components. The output of the matched filters is then down-sampled to obtain the received QAM symbol. Finally, the symbols are equalised and decoded to recover the transmitted bit stream.

CAP transmission is susceptible to a non-ideal channel frequency response, such as a non-flat magnitude response or nonlinear phase response, as this distorts the spectrum of the transmitted signal and affects the orthogonality of the I and Q introducing ISI in the link [49]. Due to the low bandwidth of the LED, this limitation becomes particularly important in UOWC links as high data rates are targeted. As a result, channel equalisation is required to overcome this issue and enable the successful recovery of the transmitted symbols. For instance, DFE consisting of a forward and a feedback filter can provide bandwidth enhancement and additionally allow easy real-time adaptation of the response, which is particularly useful in the case of time-varying channel responses. The most common forward filter is the finite impulse response (FIR) filter which consists of delay lines and taps with variable tap coefficients [60]. The optimum values of the equaliser tap coefficients depend on the channel response and therefore need to be optimized through a training process using appropriate algorithms such as the least mean squares (LMS) and RLS algorithms [61].

Another inherent disadvantage of CAP is its sensitivity to timing jitter [57]. CAP signals to exhibit a small horizontal eye-opening which is a direct result of the use of the orthogonal pulse shaping functions. There are some techniques to mitigate the issue, by using an appropriate algorithm to optimize the decision at the receiver, and an additional synchronization circuit at the receiver is used in this work based on [62].

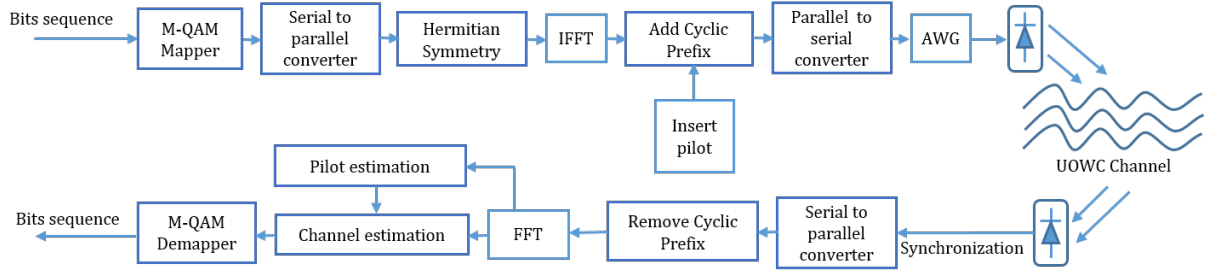


Figure 3.5: The block diagram of QAM-OFDM transceiver

3.5.2.2 Orthogonal Frequency Division Multiplexing Modulation

For OFDM applied in optical communication, the OFDM signal must be represented as intensity which means the modulated signal must be both real and positive but conventional OFDM waveforms in RF communications are both complex and bipolar [63]. Hence, Hermitian symmetry is then imposed on the OFDM subcarrier frame to realize real-valued OFDM waveforms [64] so that OFDM for optical communication as a modulation technique that is commonly used in UOWC, including [65, 66] and there are multiple variants of OFDM introduced in [67]. In this thesis, the direct current biased optical orthogonal frequency division multiplexing (DCO-OFDM) (I.E. conventional OFDM) is used to transmit QAM is considered. Here, DCO-OFDM uses a direct current (DC) bias to shift the negative real-valued QAM-OFDM samples into positive for transmission.

Figure 3.5 shows the block diagram of OFDM. A random bits sequence is generated and then mapped onto M -QAM constellation, obtained QAM symbols are then distributed across the number of subcarriers (N_{sub}). Next, Hermitian symmetry is applied to the subcarrier block before using the inverse fast Fourier transforms (IFFT) to make the symbols into a serial time domain that the time-continuous transmitted signal contains no imaginary component. In addition, subcarriers at the first and half of the frame size are set to zero because of the direct current bias. An adequate length of cyclic prefix (CP) symbols is added to the front of each OFDM block before transmission in order to reduce the impact of ISI by the computationally efficient single-tap equaliser. Then, the OFDM signal is then made unipolar by the addition of DC using a bias-T. At the receiver, the encoding process is reversed, removing CP, before a fast Fourier transform (FFT) is applied to return the symbols to the frequency domain. The frequency response of the pilot is estimated and the extracted signal is equalised, and finally demodulated and the transmitted bits recovered after the M-QAM demapper, BER is calculated

based on the demodulated binary stream [68].

The bandwidth of QAM-OFDM, B_{OFDM} , can be expressed [69]:

$$B_{OFDM} = D_b(N_{sub} + N_{CP}) / (2 \sum_{k=1}^{\frac{N_{sub}}{2}} \log_2 M) \quad (3.9)$$

where the k is number of the subcarriers, (N_{CP}) is the number of samples in the CP.

OFDM aims to solve the ISI issue introduced by a bandwidth-limited channel but has the drawbacks of the high peak-to-average power ratio (PAPR) and sensitivity to phase noise and frequency offset [63]. A small OFDM frame size results in less statistical significance, making decoding difficult; large sizes result in high PAPR, making the power efficiency of the transmission poor [64].

3.6 State of the Art in LED-based UOWC

The state-of-the-art demonstrates the recent experimental achievements of LED-based UOWC in terms of the highest data rate, the longest link distance, types of LED, channel conditions, and modulation schemes. Table 3.2 integrates the results into a list of selected LED-based experimental works in chronological order to be state of the art in UOWC. Considering the different working conditions, they will be discussed separately to present the state of the art in LED-based UOWC.

For LED-based UOWC systems reported in recent years, the distance of the maximum link is 10 m in reference [15, 70]. Li et al. using a single commercial blue LED (several MHz) for non-return-to-zero (NRZ)-on-off keying (OOK) (real-time) and 4-PAM, respectively reaching in turbid water at 25 Mbps and in clear water at 400 Mbps. The 4-PAM transmission demonstrates the use of a digital linear pre-equaliser can effectively reduce the ISI, without introducing any complex signal processing. In [65], the authors also investigated the same transmission link over a distance of 10 m but using OFDM with a bit-loading algorithm, achieved a data rate of 158 Mbps in the daytime and 205 Mbps in the nighttime. The maximum data rate achieved with a LED is 20.09 Gbps, utilizing a 4×4 LED array with different light wavelength division multiplexing (WDM) transmission for probabilistic-shaping (PS) – bit loading - discrete multi-tone (DMT) modulation, as reported in [14]. To minimise the attenuation of pure water, the

author selected the wavelength range from 456 nm to 660 nm. The highest achieved data rate for the chip of LED array is 3.16 Gbps at 660 nm with a low output power (17.8 mW).

Instead of using spectral efficiency modulation to overcome the limited bandwidth of common LED, Micro-sized LED (μ -LED) based on III-nitride semiconductors - such as Gallium nitride (GaN) used in [71, 72] - have high modulation bandwidth of up to several hundreds of MHz. Additionally, μ -LEDs offer a low resistance-capacitance (RC) delay contributing to a high modulation bandwidth ($1/(2\pi RC)$) [73]. 2 Gbps of data rate is achieved in [71] with μ -LED technology and the RNZ-OOK modulation technique. It presents that the modulation bandwidth of a 3m air-underwater system increases as the current density increases up to 1.03 GHz.

Recently, a mini-LED has been proposed to provide high bandwidth transmission (like a μ -LED) with lower power requirements (like a traditional LED). The author in [35] presents a higher emitted optical power, the UOWC system using 4-PAM has the lowest BER at 50 mA and achieved a data rate at 3.8 Gbps over the distance of 2 m link. Furthermore, the Volterra equaliser used by the author improves the data rate up to 4.4 Gbps at a BER of 3.6×10^{-3} .

Table 3.2: Selected state-of-the-art experimental works in LED-based UOWC, noting the optical source, detector, link distance etc.

Year	Data rate	Light source	Receiver	Link distance	Water type	BER	Modulation scheme	Reference
2016	25 Mbps	Blue LED	APD	10 m	turbid water	$< 10^{-4}$	NRZ-OOK	[70]
2016	745 Mbps	Blue LED	APD	2 m	tap water	2.4×10^{-3}	64-QAM-OFDM	[74]
2017	400 Mbps	Blue LED	APD	10 m	tap water	$< 7\%$ FEC	4-PAM	[15]
2017	800 Mbps	μ -LED	PIN	0.6 m	pure water	1.3×10^{-3}	OOK	[72]
2018	205 Mbps	Blue LED	PMT	10 m	harbour water	3.8×10^{-3}	OFDM	[65]
2018	2.175 Gbps	Green LED	2×PINs	1.2 m	pure water	$< 7\%$ FEC	64-QAM-DMT	[75]
2019	3 Gbps	Blue LED	PIN	1.2 m	tap water	3.8×10^{-3}	16-QAM-OFDM	[36]
2019	15.17 Gbps	RGBYC LED	PIN	1.2 m	clear water	3.8×10^{-3}	64-QAM-DMT	[76]
2020	20 Mbps	Blue LED	APD	5 m	not state	$< 3 \times 10^{-3}$	RNZ-OOK	[77]
2020	20.09 Gbps	4×4 LED array	PIN	1.2 m	pure water	$< 11\%$ FEC	WDM-DMT	[14]
2020	2 Gbps	Blue μ -LED	APD	2 m	tap water	2×10^{-3}	NRZ-OOK	[71]
2022	3.8 Gbps	μ -LED	APD	2 m	not state	3.7×10^{-3}	4-PAM	[35]
2022	6.9 Gbps	Blue mini-LED	APD	2 m	fresh water	$< 2 \times 10^{-3}$	8-PAM	[13]

3.7 Summary

An LED-based UOWC system consists of an optical transceiver and a water conditional channel. The main component of the transmitter is LED as the intensity modulation light source. The receiver is used to convert the received optical signal into an electrical signal. The recent decade study of LED-based UOWC systems is mainly focused on modulation schemes, LED types, and equalisation technologies as seen in the works of recent publications. The modulation schemes mentioned like PAM and QAM-OFDM are commonly used in studies, but CAP is not usual so it is significant to fill in the gap. The purpose of this chapter is to understand the UOWC system and challenges, and also highlight the state of the art.

Chapter 4

Equalisation techniques

4.1 Introduction

Equalisation techniques are signal processing operation that aims to minimize ISI. The ideal equaliser enables full compensation for the distortion caused by the channel. Here, the convolution of the response produced by the equaliser and channel response is one. i.e., the received signal $y(t)$ may be expressed as:

$$y(t) = x(t) \otimes h(t) + n(t) \quad (4.1)$$

where $h(t)$ is impulse response of channel, $n(t)$ is noise, $x(t)$ is transmitted signal, $\otimes$ is convolution operation. The equaliser output $h_{eq}(t)$ aims to estimate the the channel, $h_{eq}(t) \otimes h(t) = 1$. The estimate is thus calculated and it is used to compensate for the distortion of the channel which leads to improving the performance of a transmission link. In practice, the output of an effective equaliser is expected to reach a reliable BER level, such as the FEC limit.

Equalisers usually can be classified as linear and nonlinear, if the equaliser does not have a feedback path, the equalisation is linear. If there is a feedback path, the equalisation is nonlinear [78]. The advantage of a linear equaliser is that it is simple to implement but the noise component is amplified in the process of eliminating ISI. Thus, the amplified noise contributes a negative gain to the SNR, which limits the achievable data rate. The nonlinear equaliser is more complex to implement, but commonly has a better performance than the linear equaliser because the noise enhancement is limited. Therefore, it is a more effective alternative scheme for those severe channel distortion conditions. Commonly, there are two types of nonlinear equalisation schemes: the decision feedback equalisation and the maximum likelihood sequence estimator (MLSE) [78]. In this study, we mainly investigate the performance of DFE for use with CAP and PAM and ZFE for QAM-OFDM.

4.2 Linear Equaliser

4.2.1 Zero Forcing Equaliser

The ZFE is a form of a linear equaliser which applies the inverse of the channel frequency response to the received signal [79]. Using this technique can remove all ISI in a noise-free case, which is useful when the ISI component is significant compared to noise. The basic idea is that for a channel with frequency response $H(f)$, the zero-forcing equaliser $H_{zfe}(f)$ is constructed by $H_{zfe}(f) = 1/H(f)$. Thus the combination of channel and equaliser gives a flat frequency response and linear phase. The main limitation in some practical conditions is that it will greatly affect enhancing the noise power [80]. As a consequence, any noise added after the channel gets boosted in the process may result in the overall SNR reduction. However, these problems can be addressed in the linear minimum mean square error (MMSE) algorithm. It attempts to minimize the mean squared error between the equaliser output and the transmitted data symbol [78]. It will not eliminate ISI completely but find a balance between the total power of the noise and ISI components in the output. The output of ZFE in frequency domain, $\hat{X}_i$, can be expressed in terms of the received signal, Y_i and frequency response of ZFE as given by [63]:

$$\hat{X}_i = Y_i H_{zfe}(f) = \frac{Y_i}{H(f)} = X_i + \frac{N_0}{H(f)} \quad (4.2)$$

where i is the subcarrier index in frequency domain OFDM frame, X_i is transmitted symbols, N_0 is noise.

4.2.2 Decision Feedback Equaliser

The conventional DFE consists of a feedforward filter and a feedback filter [32]. The feedback filter offers feedback, which is summed with the detected symbols to provide input to a decision circuit. The process of DFE is illustrated in a block diagram in Figure 4.1. The principle is that if the detected symbols are known, the updated weight coefficient by error factor will help to remove the ISI since the past decision made symbol by symbol is assumed correct. Thus, the updated weight coefficient assists the decision circuit to make a correct decision on future unknown symbols so that the impact of ISI can be mitigated. The output of the DFE equaliser

can be expressed as [81]:

$$\hat{y}(n) = \sum_{i=0}^{J_{ft}-1} w(i)y(n-i) - \sum_{i=1}^{K_{bt}} \tilde{w}(i)\check{d}(n-i) \quad (4.3)$$

where $\hat{y}(n)$ corresponds to the output of the equaliser, whilst $y(n)$ and $w(i)$ are the input and tap gains for the feed-forward filter, $\check{d}(n)$ and $\tilde{w}(i)$ are the decisions for previously detected symbols and tap gains for feedback filter. J_{ft} and K_{bt} denote the tap numbers of both terms, respectively. DFE will be employed for CAP and PAM in further experiments.

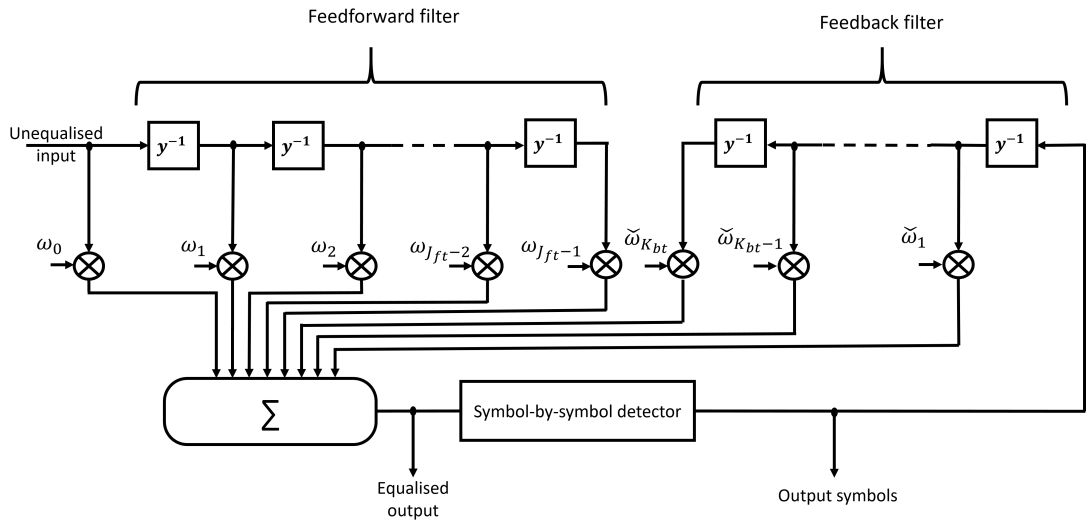


Figure 4.1: Decision feedback equaliser.

4.3 Nonlinear Equaliser

4.3.1 Volterra Series-based DFE

The purpose of VDFE is to further mitigate the intrinsic static and dynamic non-linearity effects, such as those caused by LEDs [82]. The format of input symbols into the feedforward filter determines whether the DFE is linear or nonlinear. In this technique, the basic linear feedforward filter, of the standard DFE, is replaced by a nonlinear feedforward filter based on the Volterra series as illustrated in the block diagram shown in Figure 4.2. This technique builds on the standard DFE with the addition of higher-order polynomial coefficients to account for the non-linear effects of the channel, at a cost of increasing the complexity of the system. This work utilises a second-order VDFE that can be expressed as [83]:

$$\hat{y}(n) = \sum_{i=0}^{J-1} a(i)y(n-i) + \sum_{i,j=0}^{Q-1} b(i,j)y(n-i)y(n-j) - \sum_{i=1}^{K_{bt}} c(i)\check{d}(n-i) \quad (4.4)$$

where $a(i)$ and $b(i, j)$ are the linear and second-order tap gains of the feed-forward filter section, respectively. $c(i)$ is the feedback filter tap gains and $\check{d}(n)$ are prior decision symbols. J , Q , and K_{bt} denote the tap numbers in each terms. VDFE will use to compare with DFE for the performance of CAP in the further experiment.

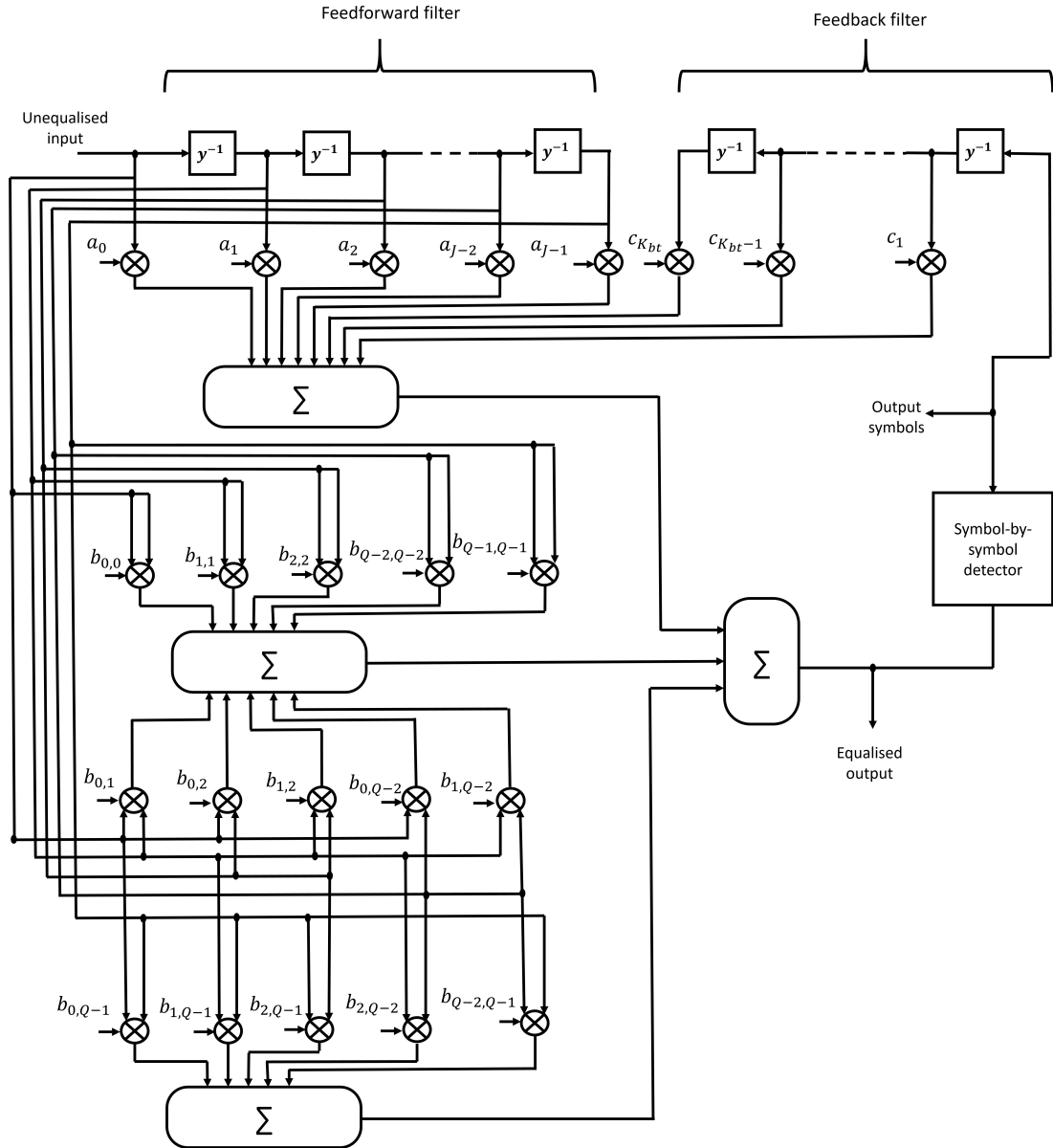


Figure 4.2: *Volterra series-based decision feedback equaliser.*

4.4 Channel Estimation

Both DFE and VDFE employ the MMSE algorithms in their channel estimation. The common MMSE algorithms are the least mean squares (LMS) and recursive least squares (RLS) [7]. LMS has lower computational complexity than RLS, but RLS exhibits extremely fast convergence [78]. This property makes RLS preferable as it means fewer training symbols are required to accurately estimate the channel. In this work, the RLS algorithm is applied for both DFE and VDFE. The RLS algorithm is expressed as follows [84]:

$$y(n) = \begin{bmatrix} y(n) \\ y(n-1) \\ \vdots \\ y(n-p) \end{bmatrix} \quad (4.5)$$

$$e(n) = d(n) - \check{d}(n) = d(n) - y^T w(n-1) \quad (4.6)$$

Where p is filter order, $e(n)$ is the error factor, $d(n)$ is the desired symbol, and T denotes a transposition operation. The weighting coefficient of the filter, $w(n)$, is updated by:

$$w(n) = w(n-1) + e(n)g(n) \quad (4.7)$$

where:

$$g(n) = P(n-1)y(n)\{\lambda + y^T(n)P(n-1)y(n)\}^{-1} \quad (4.8)$$

and

$$P(n) = \lambda^{-1}P(n-1) - g(n)y^T(n)\lambda^{-1}P(n-1) \quad (4.9)$$

where $1 > \lambda > 0$ is the forgetting factor which applies an exponentially smaller weight to older error samples, and P is the inverse correlation matrix. Using the equations of 4.6 - 4.8, the weight coefficient of the filter can be updated with the input of $y(n)$.

Here, the equalisation processing as shown in Fig 4.3. There are two operation steps including training and tracking. In fig 4.3, training symbols as known symbols ($d(n)$) of part of received symbols ($y(n)$) are using the RLS algorithm to adjust the weight values to minimize the mean square error at each weight update. As the sequence of decision symbols comparing to known ideal symbols, the error ($e(n)$) gradually decrease, the weighting coefficient is possible for the equalizer to track the unknown symbols.

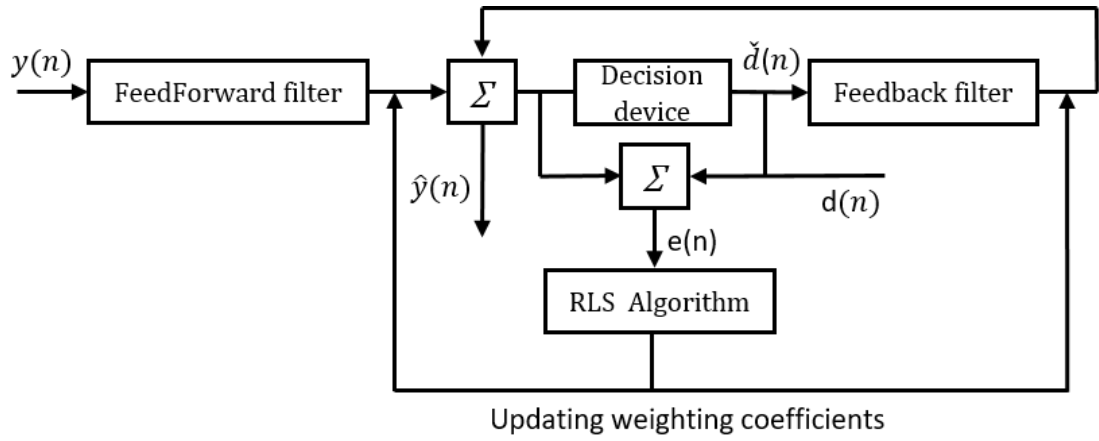


Figure 4.3: DFE operation scheme

4.5 Summary

In this chapter, we have introduced the equalisation techniques that address the ISI caused by the limited bandwidth based on LED optical communication system in this work. The DFE, VDFE and ZFE are designed for solving the ISI but with different characteristics. VDFE is a further variation on the DFE, which enables against the nonlinearity of LEDs at the expense of complexity and loss of speed. Thus, in order to investigate the performance of CAP in the UOWC, DFE and VDFE will be employed for comparing the improvement of CAP in clear water first. Next, OFDM is a multi-carrier technique to implement the QAM in this work, ZFE will be done in the frequency domain rather than in the time domain. QAM-OFDM serves as a comparator to measure the performance of CAP. PAM is a simple and common modulation scheme that is used in the UOWC, it will be applied DFE in the turbid water condition to compare with CAP.

Chapter 5

System Characterisation of LED-based UOWC

5.1 Introduction

In this chapter, the LED-based UOWC system is characterised to gain an understanding of the channel before data transmission is investigated in chapter 6. The LED used in this study is blue LED, selected because the region of lowest attenuation in seawater occurs at wavelengths between 450 nm and 550 nm (blue-green region) [5]. The experiments are carried out in the laboratory using an underwater channel emulator (UCE). The UCE consists of a tank with dimensions $1.5 \times 0.5 \times 0.5 \text{ m}^3$ in which the water conditions can be controlled to emulate real-world UOWC channels.

5.2 Experimental Set-Up

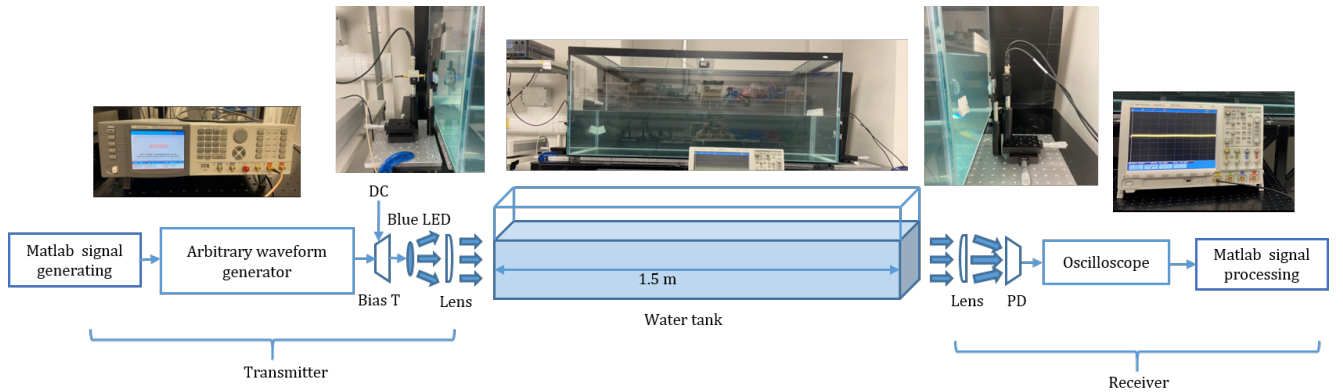


Figure 5.1: The experimental block diagram and setup used in this study, showing the transmitter; underwater channel emulator (UCE); and receiver stages of the system.

The experimental block diagram and setup used throughout this study are pictured in Figure 5.1. The signal modulated by PAM, CAP and OFDM is generated offline in Matlab then sent to

a Keysight 81180A arbitrary waveform generator (AWG), and transmitted via a VLMB1500-GS08 blue LED applied 20 mA. Light emitted from the LED is collimated using a plano-convex lens before propagating through the UCE. The UCE is filled with 200 L of water, and the turbidity of the water is controlled throughout the study by adding crushed antacid tablets. At the receiver, a plano-convex lens is used to focus the light beam onto a Thorlabs PDA10A-EC photo detector (PD) with 150 MHz bandwidth to convert the signal from the optical to the electrical domain. The electrical signal is sampled by a Keysight MSO7104B oscilloscope. Finally, signal processing is carried out offline using Matlab software. The signal is synchronized before reverting to the symbols. These symbols are then mapped back to the constellation after equalisation.

5.3 Received Optical Power Characterisation

Figure 5.2 shows the relationship between received optical power and electrical bias current after propagating through a clear water channel. The power versus current curve is most linear between 15 and 25 mA of the LED, which is corresponding to the information on the device datasheet. The non-linearity gradually appears as the drive current increases beyond 25 mA until it will reach a saturation region. Resultantly, in order to keep the LED operating within its linear region, the bias current is selected to be 20 mA through the rest of this study. This will yield an average received power of $577 \mu W$ in clear water.

5.4 Turbid Channel Conditions

The UOWC channel presents a challenge to the development of reliable communication systems. The absorption and scattering of light due to the properties of water and suspended particles limit the transmission distance of UOWC [4, 85]. Turbid water conditions are then created within the UCE by adding crushed antacid tablets (500mg/tablet). The effect of suspended particles on the UOWC link can be quantified in terms of the extinction coefficient, c' . For a non-monochromatic light source, such as an LED, (2.11) can be rewritten to remove the wavelength dependency. This effective extinction coefficient, c' , is calculated relative to the optical power in free-space, P_0 :

$$c' = -\frac{1}{R} \ln \frac{P_r}{P_0} \quad (5.1)$$

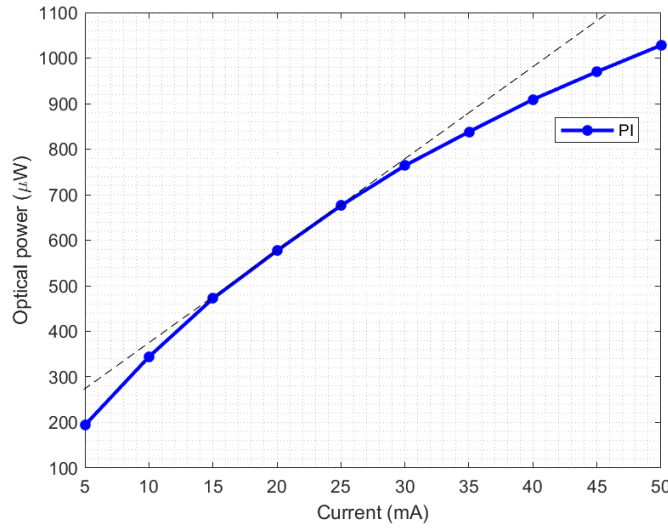


Figure 5.2: Graphical illustration of the received optical power vs bias current of the LED (VLMB1500-GS08) after propagating through the UCE under clear water conditions

where $R = 1.5$ m is the propagation distance, P_r is the total optical power measured at the receiver.

Using (5.1) and a measured free-space $P_0 = 0.922$ mW, the extinction coefficient effective within the link is estimated to quantify the effect of turbidity. Figure 5.3 shows the c' , calculated from P_r , plotted against antacid concentration (C) fitted with a third-order polynomial curve.

$$c' = P_1 C^3 + P_2 C^2 + P_3 C + P_4 \quad (5.2)$$

Fitting coefficients, $P_i, i = (1, 2, 3, 4)$ and the R^2 metric of fit are displayed in Table 5.1. It is shown by an $R^2 = 0.999$ that the third-order polynomial provides a good description of the relationship between c' and antacid concentration. In Figure 5.3, it is shown that c' increases with an increase in antacid concentration and selected 4 points as study channel conditions for further investigation within this study.

Figure 5.4 presents photographs of the selected channels taken from the transmitter side, facing the receiver in the conditions of clear tap water, turbid 1, turbid 2, and turbid 3. With the increase of the concentration of particles in water, the visibility of the receiver gradually decreases until the receiver is almost invisible in turbid 3. This provides a visual representation of the effect of turbidity on the link visibility and channel gain. In Table 5.2 the case study water

conditions are displayed and related to similar Jerlov water types.

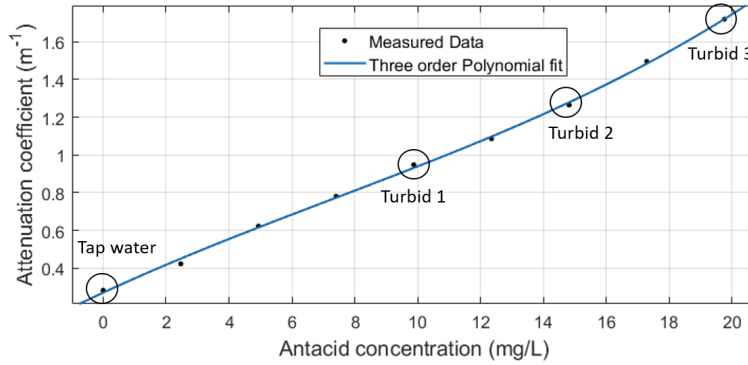


Figure 5.3: Antacid concentration against attenuation coefficient.

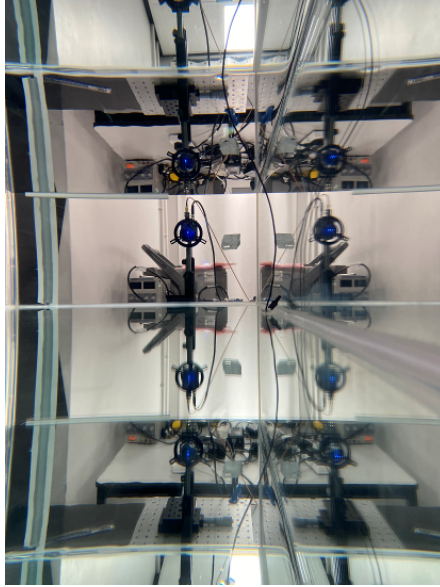
Table 5.1: Fit parameters for Fig 5.3

Coefficients	P_1	P_2	P_3	P_4	R^2
Polynomial	$8.612e^{-5}$	$-1.894e^{-3}$	0.0773	0.2699	0.999

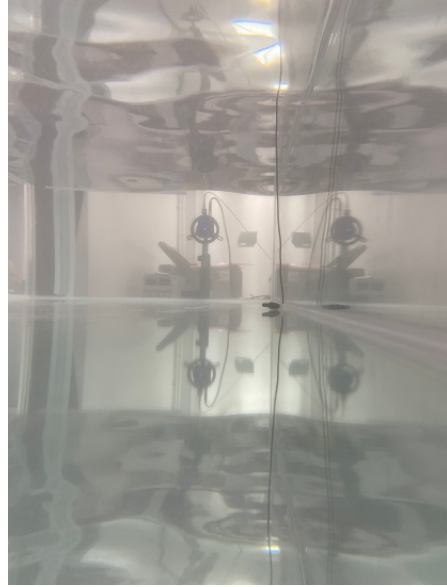
Additionally, the effect of turbidity on the received signal is investigated by transmitting a 1 MHz sine wave through the channel. In each channel, the V_{pp} of the received signal and the degradation of amplitude for each condition of turbid water compared to tap water are shown in Table 5.3. With the increase of turbidity, the absorption and scattering in water are increased and the signal degrades further. This is observed during signal transmission in the form of a reduction in the received SNR.

5.5 Frequency Response

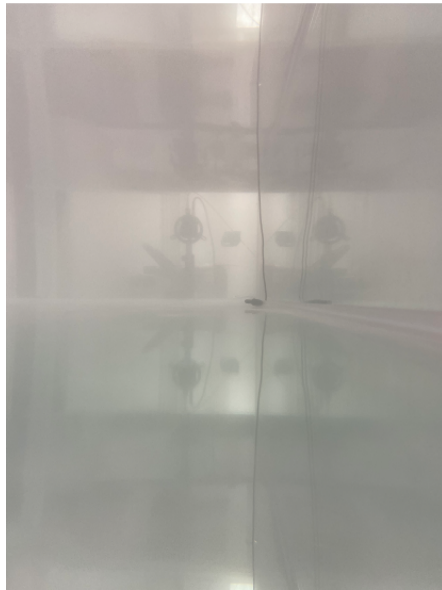
Figure. 5.5 shows the normalized frequency response of the LED-based UOWC link in clear water conditions. A sine wave with a frequency range from 1MHz to 50MHz is transmitted via the channels using the LED with V_{pp} of 0.5 V obtained from the PD at the receiver. Finally, the channel gain in dB is presented in Figure 5.5. It exhibits characteristics of a low pass filter with the -3 dB bandwidth in clear water that is approximately 14 MHz. This limited bandwidth means that spectrally efficient modulation techniques are required to avoid ISI induced at high transmission rates. Due to the suspended particles settling, it was not possible to record an accurate frequency response in turbid water using this method. The non-normalized and



(a) Tap water



(b) Turbid 1



(c) Turbid 2



(d) Turbid 3

Figure 5.4: *Turbid transmission channels.*

Table 5.2: *Experimental conditions of case study turbid water conditions and their closest Jerlov water type.*

	C (mg/L)	P_r (mW)	c' (m^{-1})	Jerlov Water Type
Clear water	0	0.577	0.2824	Jerlov II
Turbid 1	7.4074	0.252	0.7814	Jerlov III
Turbid 2	14.8148	0.113	1.2646	Jerlov III
Turbid 3	19.7531	0.053	1.7206	Jerlov 3C

Table 5.3: *The attenuation of the channel to the sine signal*

Channel	Tap	Turbid 1	Turbid 2	Turbid 3
V_{pp}	865 mV	275 mV	94 mV	36.8 mV
Degradation	N/A	68.2%	89.1%	95.7%

normalized frequency response of system links in turbid conditions as shown in Fig 5.6. In Fig 5.6 (a), the -3 dB bandwidth increases as turbidity increases. It can be explained in Fig 5.6 (b), measurement goes with the particles settling down so that when the measurement at high frequency, the channel gain is higher than the actual result. However, the clear water measurements correspond with the known bandwidth of LED, suggesting that this is the main cause of the bandwidth limitation in the system.

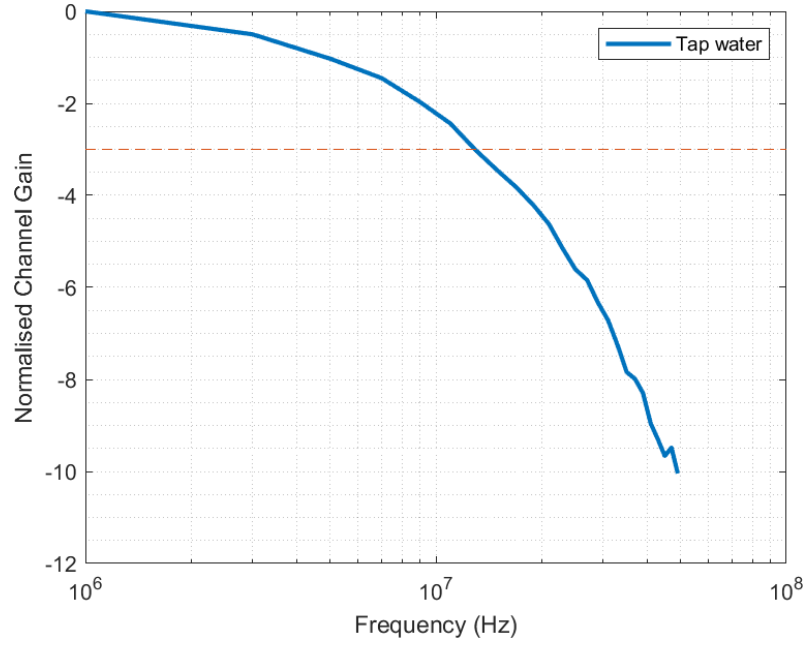


Figure 5.5: *The normalised frequency response of the system in clear water link.*

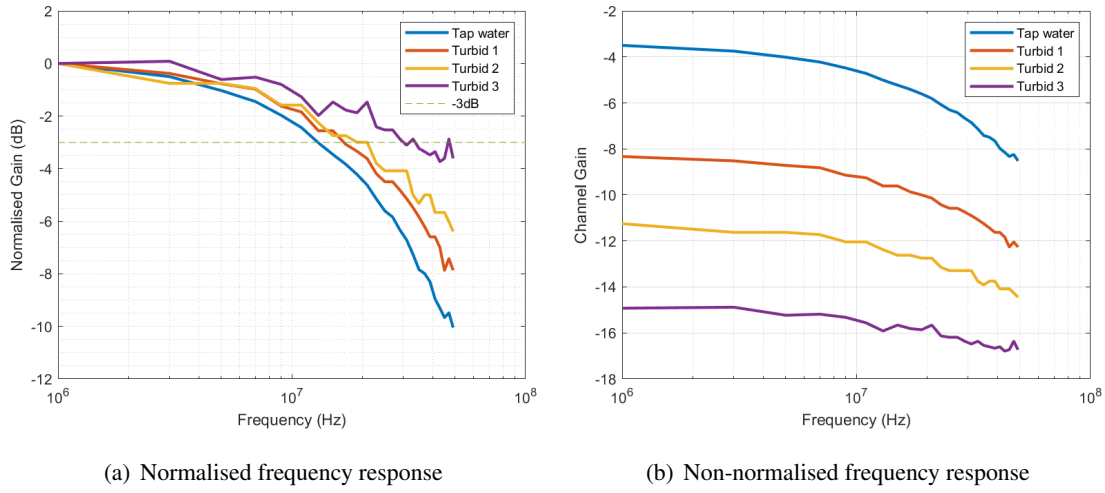


Figure 5.6: *The frequency response of the system in turbid water links.*

5.5.1 SNR of LED in Turbidity Channels

5.5.1.1 Error Vector Magnitude

Error vector magnitude (EVM) is a measure used to quantify the quality of digital data transmission. It can evaluate the difference between actual symbols and ideal symbols by computing the root-mean-squared (RMS) average amplitude of the error vector. The transmitted symbols have precise locations in the constellation, but the actual received symbols will deviate from the ideal positions due to some factors such as noise. In other words, EVM is a measure of how far these received symbols deviate from their ideal positions. The EVM can be expressed as [86]:

$$EVM_{RMS} = \sqrt{\frac{\frac{1}{N} \sum_{n=1}^N |S_r(n) - S_t(n)|^2}{P_0}} \quad (5.3)$$

where N is the number of symbols over which the value of EVM is measured, $S_r(n)$ is the normalized received n th symbol which is corrupted by Gaussian noise, $S_t(n)$ is the ideal/transmitted value of the n_{th} symbol, and P_0 is either the maximum normalized ideal symbol power or the average power of all symbols for the chosen modulation.

Assuming that OFDM subcarriers are narrow enough that the channel can be considered AWGN, the difference between $S_r(n)$ and $S_t(n)$ will be equal to the noise component of the channel. Therefore, the EVM may be rewritten as:

We assume that the number of transmitted symbols is large enough since the signals are only corrupted by AWGN, equation 5.3 can be simplified as:

$$EVM_{RMS} \approx \sqrt{\frac{N_0}{P_0}} = \sqrt{\frac{1}{SNR}} \quad (5.4)$$

where N_0 is the noise power spectral density. That means the SNR can be calculated as:

$$SNR = \frac{1}{EVM^2} \quad (5.5)$$

Since the attenuation of the signal power is mainly caused by the increase of channel turbidity, channel turbidity is the main factor affecting the SNR value. Figure 5.7 shows the received SNR for each subcarrier obtained via the transmission of a 4-QAM-OFDM signal. It can be seen that the SNR is not constant across all subcarriers, in-line with the expectation given the frequency response of the clear water link. It can further be seen that the SNR reduces as the subcarrier index increases and the entire performance of SNR go down as turbidity increases. Expectedly, the SNR in the turbid 3 condition is far lower than in other channels, which corresponds to Jerlov 3C having a greater effect on signal attenuation. This significant decay indicates the attenuation coefficients of water conditions exceeding the turbid 3 condition may be too large to support a reliable communication link. Table 5.4 shows the mean EVM and SNR for the LED.

Table 5.4: *The mean EVM and SNR of various channels*

Channel	Tap	Turbid 1	Turbid 2	Turbid 3
Mean EVM	0.2144	0.2353	0.2605	0.3095
Mean SNR (dB)	14.6	13.8	12.5	10.4

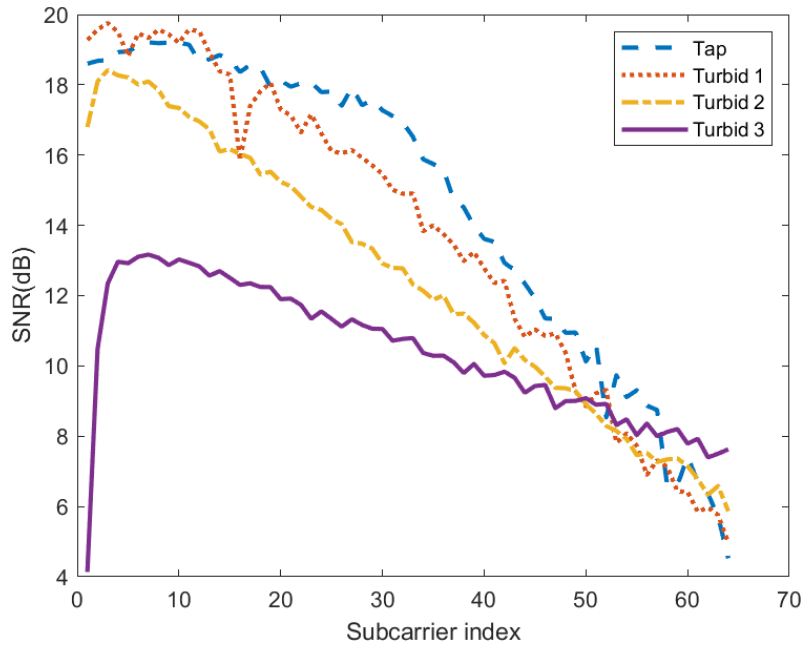


Figure 5.7: The SNR of subcarrier using 4-QAM-OFDM transmission via various channels

5.6 Summary

In this chapter, we have discussed the design of the LED-based UOWC system. The LED shows its nonlinear property as the bias current increases. The LED is controlled to work within the linear region at 20 mA. The water channel conditions consisted of clear water and three various turbidity levels of water. The extinction coefficient for these four conditions is calculated by the measured optical power at the transmitter and receiver. The results against the antacid concentration that fits in the third-order polynomial function. The frequency response of light in free space and clear water has been compared which shows the bandwidth is narrow, requiring an efficient modulation scheme to support a high data rate. Additionally, SNR was obtained based on the EVM by using 4-QAM-OFDM transmission via these channels.

Chapter 6

The Empirical Comparison of Modulation Techniques for UOWC

6.1 Introduction

After characterising the UOWC system in Chapter 5, this chapter aims to investigate the performance of spectrally efficient modulation schemes, namely PAM, CAP, and QAM-OFDM, in underwater channels in order to overcome the limitations of both the LED and the UOWC channel. In this investigation, the comparison of CAP and QAM-OFDM has been measured in clear water. Next, PAM, CAP, and QAM-OFDM are analyzed in turbid water conditions. Additionally, bit Power loading applied basic OFDM aims to find the improvement of data transmission via both water conditions. Finally, this research is summarised in terms of the maximum data transmission performance across LED-based underwater channels.

6.2 Comparison of CAP and QAM-OFDM in Clear Water

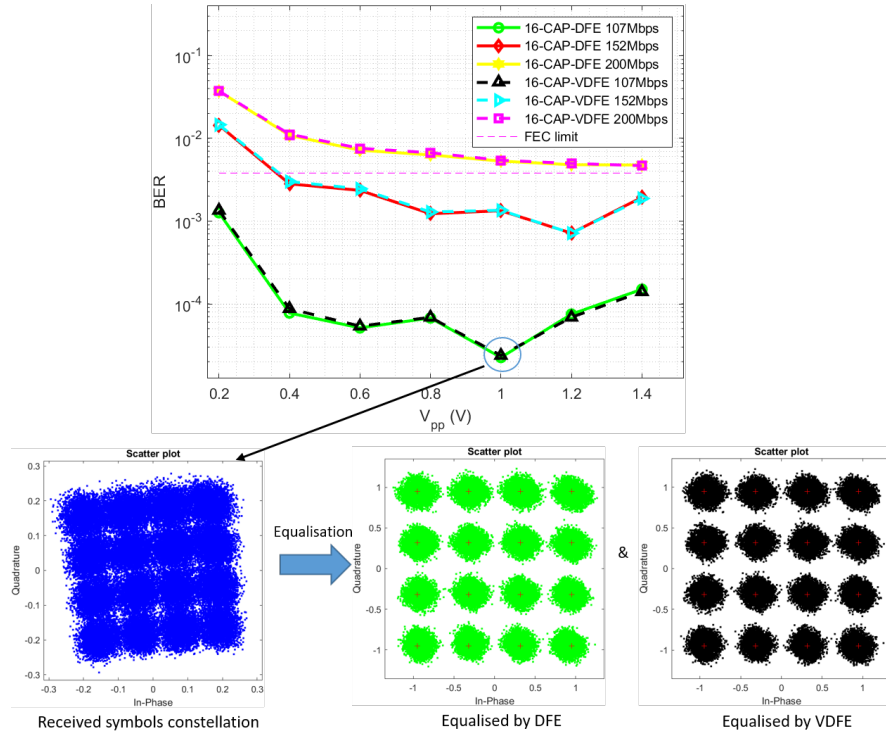
6.2.1 Comparison of CAP using DFE and VDFE

The performance of the DFE and VDFE equalisation techniques in CAP is compared experimentally. In this comparison, the CAP signal is generated using orthogonal filters with a roll-off factor and symbol span equal to 0.15 and 10, respectively. The sample rate is fixed to 800 MSam/s and the data rate is controlled by the number of samples per symbol (sps). During the data transmission, the equalisers under test are trained using the first 2000 symbols out of a total of 5×10^4 .

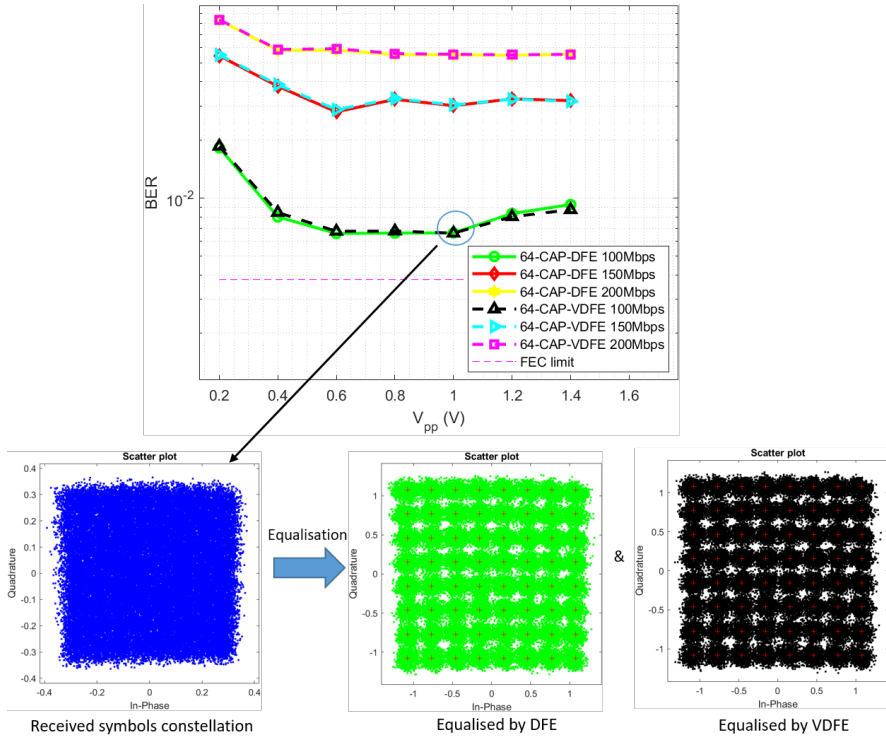
Figure 6.1 show the curves of BER versus V_{pp} for CAP with $M = \{16, 64\}$, respectively, operating at bit rates of $\{100, 150, 200\}$ Mbps. Across all data rates considered the BER curves from both equalisation techniques are overlaid. The BER target is selected at the International Telecommunication Union's (ITU's) recommended error floor ($\text{BER} = 3.8 \times 10^{-3}$) or called the FEC limit in this study [56], as below this limit coding techniques can make the transmission

effectively error-free. In Figure 6.1a, both equalisation techniques achieve the FEC with a $V_{pp} < 0.2$ V and 0.4 V for 100 Mbps and 152 Mbps, respectively. However, when the bit rate is 200 Mbps the FEC cannot be achieved as the BER curve approaches an error floor above a BER of 4×10^{-3} . Similarly, in Figure 6.1b it is shown that 64-CAP cannot be supported below the FEC under any of the experimental conditions considered in this work. This suggests that the channel does not have enough SNR margin for CAP with $M \geq 64$.

The symbol constellation diagrams of the received CAP signal before equalisation at 100 Mbps and $V_{pp} = 1$ V for 16 and 64-CAP are inlaid at the bottom of Figure 6.1(a) and 6.1(b), respectively. Here, it can be seen that there is a phase rotation introduced by the link in the 16-CAP transmission. There are small gaps between symbol clouds for 16-CAP but no such visible gaps for 64-CAP, further suggesting the SNR requirements of 64-CAP are not met. Also inlaid in Figure 6.1(a) and 6.1(b) are the post-equalisation constellation plots for both techniques under test. For 16-CAP, it can be seen that the phase rotation is removed and the decision boundaries between symbols are clear after equalisation. For 64-CAP, the decision boundaries are more clear than before equalisation, but they are still not defined enough for adequate error performance. The 2nd order VDFE is expected to outperform a linear equaliser in the presence of non-linear distortion. However, since the LED is biased in the very linear region of its transfer curve, the linear and VDFE have identical performances. Due to the similarity in error performance, the rest of this study will consider only the simpler DFE equalisation technique.



(a) 16 CAP



(b) 64 CAP

Figure 6.1: The BER vs V_{pp} of M-CAP using DFE and VDFE

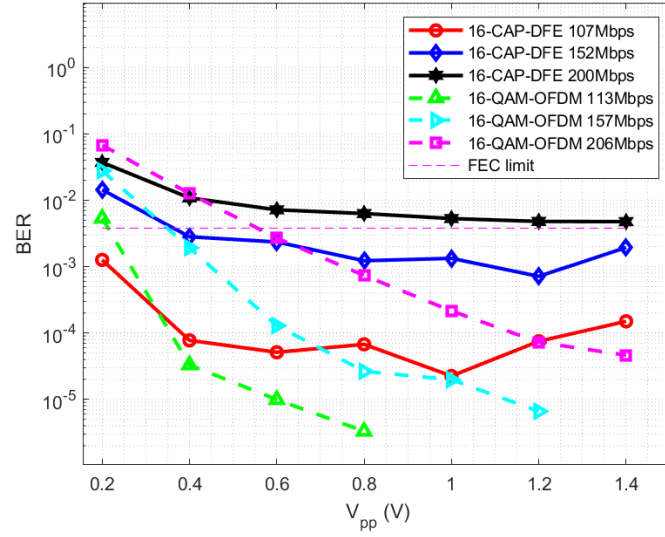
6.2.2 Comparison of CAP and QAM-OFDM

Next, the performance of CAP with DFE is compared with that of OFDM. The two techniques are both used to implement QAM modulation and OFDM is most common in literature. CAP with DFE is compared to the commonly used OFDM technique. The OFDM transmission is implemented with a fixed sample rate of 2 GSam/s with the data rate controlled by changing the sps , as in CAP transmission. Again, $M = 16$ and 64 are considered for QAM-OFDM.

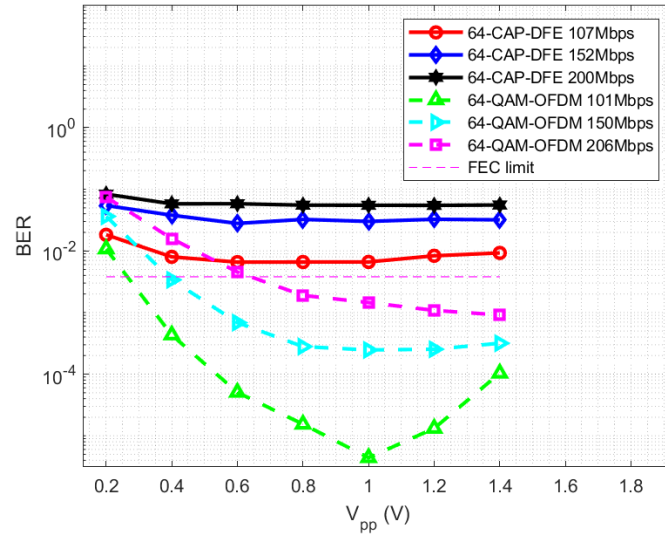
The error performance of CAP is compared to that of QAM-OFDM in Figure 6.2. When the modulation order is equal to 16, CAP performs better than QAM-OFDM when V_{pp} is low (0.2 V). When the value of V_{pp} increases, 16-QAM-OFDM outperforms 16-CAP at each data rate considered. QAM-OFDM can achieve error performance below the FEC limit in all data rates considered, this contrasts with CAP which can only support 107 Mbps and 152 Mbps with $M = 16$.

When a modulation order of 64 is considered the difference between the two schemes becomes more apparent. In Figure 6.2b, it is shown that QAM-OFDM can support all data rates considered within the FEC limit. However, in this case, 64-CAP cannot be supported, suggesting that the bandwidth and SNR requirements cannot be satisfied in this link. This implies that OFDM will be preferred for the same modulation order.

Experimental results show that in 16-CAP and 64-CAP, both DFE and VDFE yield similar error performance when operated in the linear region of the LED. Further, OFDM outperforms CAP overall data rates considered in this study, apart from the case of low V_{pp} .



(a) 16 CAP



(b) 64 CAP

Figure 6.2: The BER plotted against V_{pp} of 64-CAP and M-QAM-OFDM

6.3 Comparison of PAM, CAP and QAM-OFDM in Turbid Water Conditions

Following the prior works, the peak-to-peak voltage (V_{pp}) and bias current are respectively set to 1 V and 20 mA, which were found to give optimal performance for CAP and QAM-OFDM. For the channel simulator, tap water ($c = 0.28 \text{ m}^{-1}$), turbid 1 ($c = 0.78 \text{ m}^{-1}$), turbid 2 ($c = 1.26 \text{ m}^{-1}$) and turbid 3 ($c = 1.72 \text{ m}^{-1}$) will be selected as the channel conditions.

The data transmission is repeated for 3 iterations of 4×10^4 symbols, and the resultant BER is averaged to obtain reliable results in the turbid UOWC channel. In this study, the bit rate (R_b) is controlled by changing both the sampling frequency and oversampling factor. The DFE is employed for PAM and CAP, while QAM-OFDM utilises single-tap ZFE.

6.3.1 PAM Data Transmission

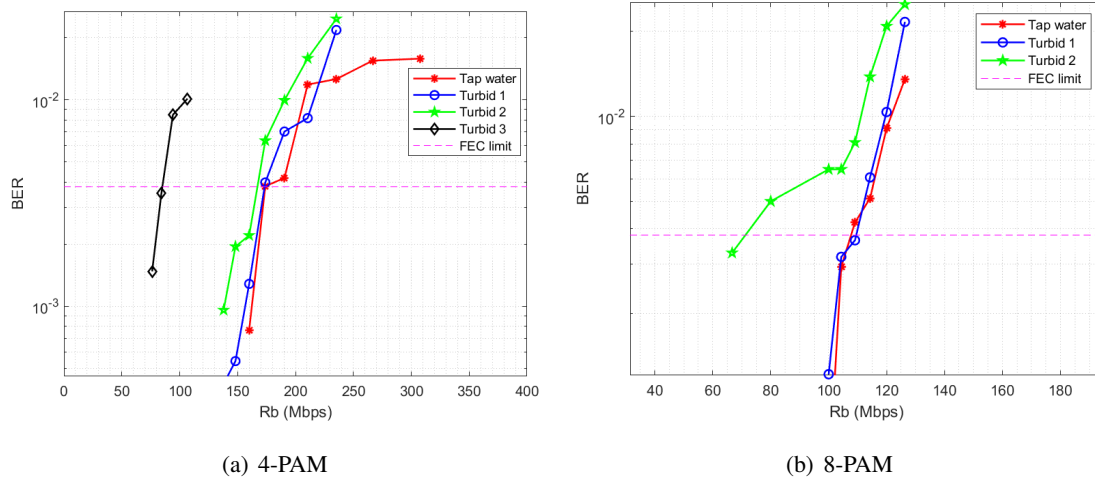


Figure 6.3: BER curves for (a) 4-PAM and (b) 8-PAM transmission in tap water and turbid water conditions.

Figure 6.3 shows the BER versus R_b curves for PAM. In Figure 6.3a, the BER performance of 4-PAM signal transmission in tap water, turbid 1 and turbid 2 is almost identical, and they reach the FEC limit at 170 Mbps. However, in the case of turbid condition 3, the transmission rate at the FEC limit is reduced to 85 Mbps. Figure 6.3b shows the performance of 8-PAM. Here, the BER performance of tap water and turbid 1 are similar, but the BER curve of turbid 2 deviates seriously. Tap water and turbid 1 can reach the FEC limit at 108 Mbps, turbid 2 can reach the

FEC limit at 71 Mbps. Whereas, turbid 3 condition cannot support 8-PAM below the FEC limit at any data rate.

6.3.2 CAP Data Transmission

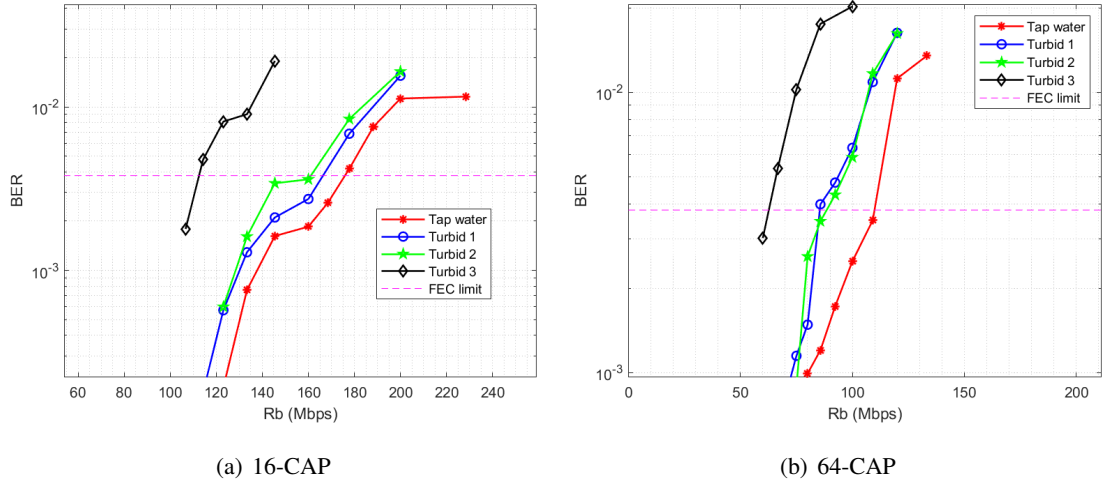


Figure 6.4: BER curves for (a) 16-CAP and (b) 64-CAP transmission in tap water and turbid water conditions.

Figure 6.4 presents the BER performance against the data rate for CAP with the $M = \{16, 64\}$ in the case study UOWC channel conditions. For $M = 16$, the BER performance has a gradually decreasing trend with the increase of absorption and scattering effects in the underwater channel. The FEC limit is achieved in tap water, turbid 1, turbid 2 and turbid 3 at the data rate of 176 Mbps, 167 Mbps, 161 Mbps and 113 Mbps, respectively.

The BER vs R_b curves for 64-CAP are shown in Figure 6.4b. The FEC limit is achieved in tap water, turbid 1, turbid 2 and turbid 3 at the data rate of 110 Mbps, 87 Mbps, 87 Mbps and 63 Mbps, respectively. Here, the drop in performance between clear tap water and turbid conditions 1 and 2 is greater than for 16-CAP. This observation can be explained by the increased SNR requirement of higher modulation orders. The channel for turbid 1 and turbid 2 show the same performance for 64-CAP. Similarly, the BER performance of turbid 3 is still strongly degraded. In CAP, the transmission rate of low-order modulation is almost twice that of high-order modulation when the FEC limit is reached. This means that the low SNR and limited bandwidth limit the modulation order that can be supported for higher modulation.

6.3.3 QAM-OFDM Data Transmission

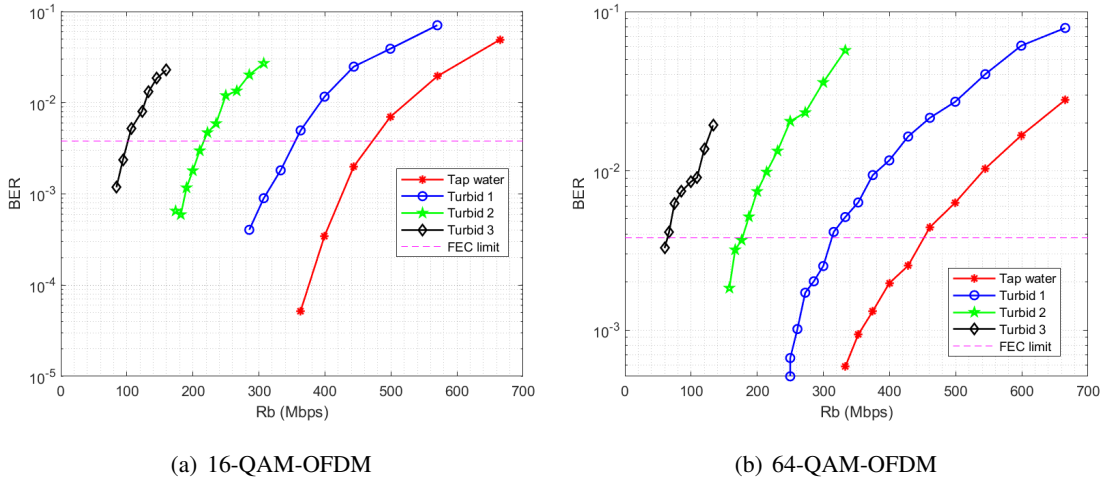


Figure 6.5: BER curves for M -QAM-OFDM transmission in tap water and turbid water channels, (a) $M = 16$ and (b) $M = 64$.

Figure 6.5 shows the BER curve for QAM-OFDM in the UOWC channel. In Figure 6.5a, the 16-QAM-OFDM reaches the FEC limit at transmission rates of 472 Mbps, 355 Mbps, 217 Mbps and 102 Mbps, respectively. In Figure 6.5b, for the higher-order 64-QAM-OFDM, the transmission rate is 452 Mbps, 313 Mbps, 177 Mbps and 64 Mbps, respectively in tap water, turbid 1, turbid 2, and turbid 3. With the increase of turbidity, the transmission rate of 64-QAM-OFDM in tap water is close to that of 16-QAM-OFDM, and it has been reduced to almost half of that at turbid 3.

6.3.4 Bit and Power Loading

Bit and power loading (BPL) is implemented to optimize the maximum transmission rate for basic OFDM. Table 6.1 presents the data rate at which 4-QAM-OFDM reaches the FEC limit in various water conditions and the improved data rate after bit power loading. In tap water, the data rate is improved by almost 18 % after bit loading. However, the improvement effect of BPL begins to decrease as turbidity increases with 8.1 % in turbid 1, -24.4 % in turbid 2 and -53.9 % in turbid 3. BPL is not as good when the SNR is low as the channel state information available when allocating bits is less accurate.

Figure 6.6 shows the bits per symbol and power-loading factor allocated to each subcarrier when the data rate reaches the FEC limit. In tap water, lower-order subcarriers can be allocated

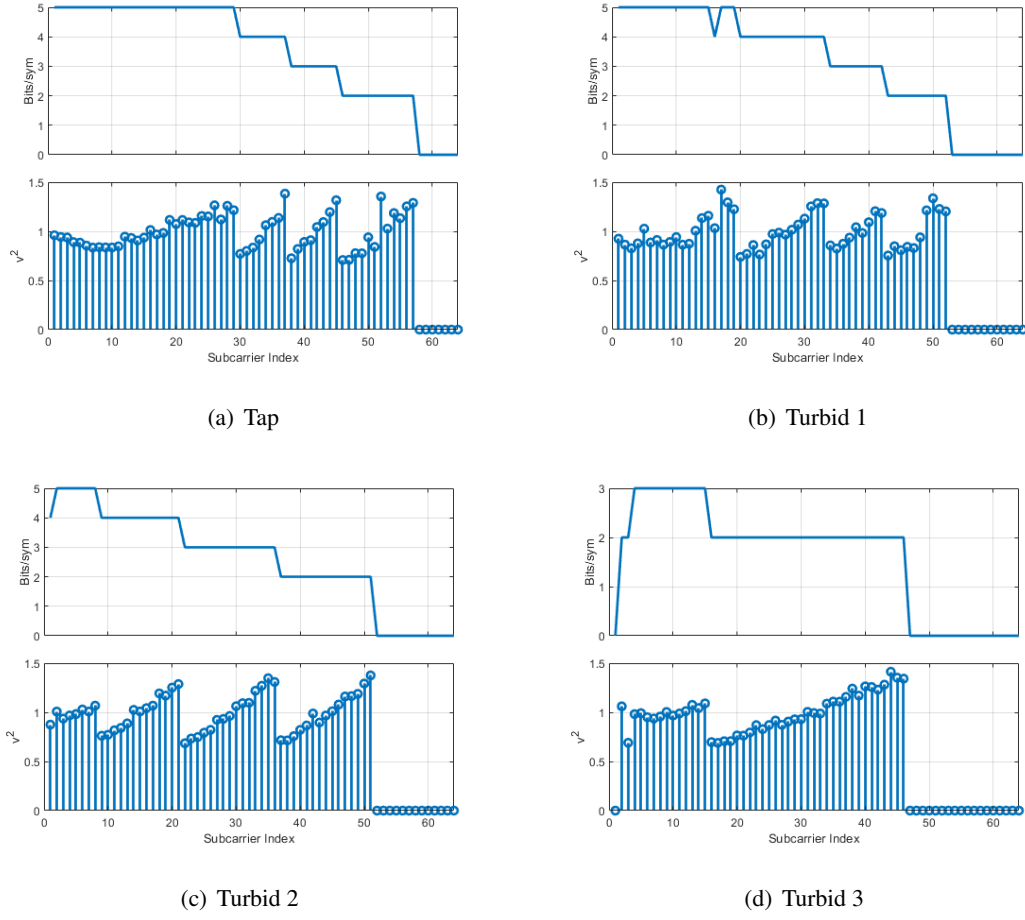


Figure 6.6: The bit allocation and voltage multiplication factor in (a) clear tap water, (b) turbid 1 (c) turbid 2 and (d) turbid 3 channel conditions.

Table 6.1: The maximum data rate achieved within the FEC limit with M-QAM data rate and the data rate achieved after implementing the bit power loading

Water type	M-QAM-OFDM	Bit Power Loading
	Data Rate [Mbps]	
Tap	472	557
Turbid 1	355	384
Turbid 2	217	164
Turbid 3	102	47

more bits per symbol, whereas subcarriers towards the higher end are nulled due to their poor SNR and BER performance. The power loading in the sections of different subcarriers block becomes balanced. With the increase of turbidity, in turbid 1, turbid 2 and turbid 3, the SNR of each subcarrier gradually decreases, so they can not support more bits per symbol. The maximum number of bits allocated is 5 bits in clear water, turbid 1, and turbid 2 water conditions. While, it drops to a maximum of 3 bits in the turbid 3 channel, which corresponds to the lower SNR for this condition as shown in Figure 5.7.

6.4 Comparison of Maximum Transmission Rates at the FEC Limit

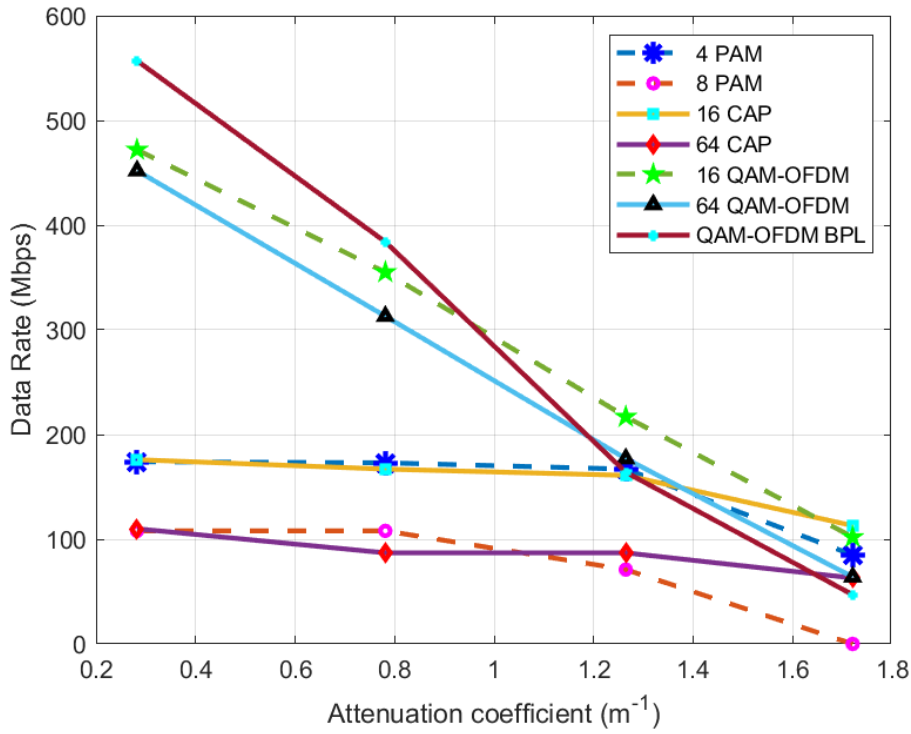


Figure 6.7: The Maximum data rate for each modulation technique at different values of attenuation coefficient.

The modulation techniques under test are compared in terms of the maximum data rate at the FEC limit achieved in this study in Figure 6.7. It can be seen that whilst the maximum data rate achieved with PAM and CAP is approximately 180 Mbps in still water, this performance is maintained up to turbid condition 3. Conversely, QAM-OFDM - with both fixed M and BPL - can achieve much higher data rates in still water but exhibit a steep drop in data rate as the turbidity increases. In still water OFDM with BPL achieves 557 Mbps compared to 47 Mbps in

turbid condition 3, whilst 16-QAM-OFDM achievable transmission rate drops from 480 Mbps to about 100 Mbps for the same conditions.

Figure 6.8 - Figure 6.15 present the BER in each subcarrier and the SNR values of each subcarrier for tap water, turbid 1, turbid 2 and turbid 3. After bit power loading, the BER performance of each subcarrier fluctuates around the FEC limit whereas prior to applying BPL, the BER was imbalanced across subcarriers. Ranging from an error-free performance in lower-ordered subcarriers with BER increasing as the subcarrier index increases. The SNR becomes flat in each subcarrier interval instead of the decreasing as subcarrier index increases.

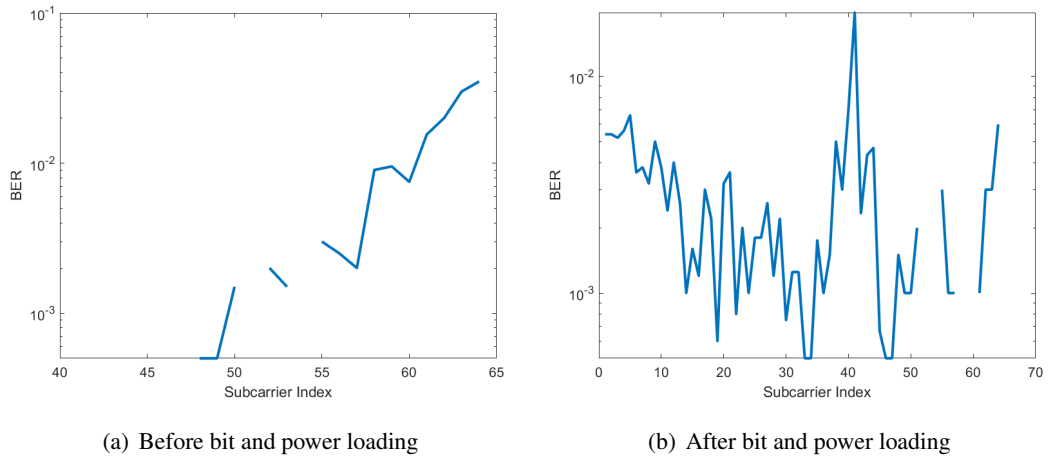


Figure 6.8: The BER performance for each subcarrier in tap water

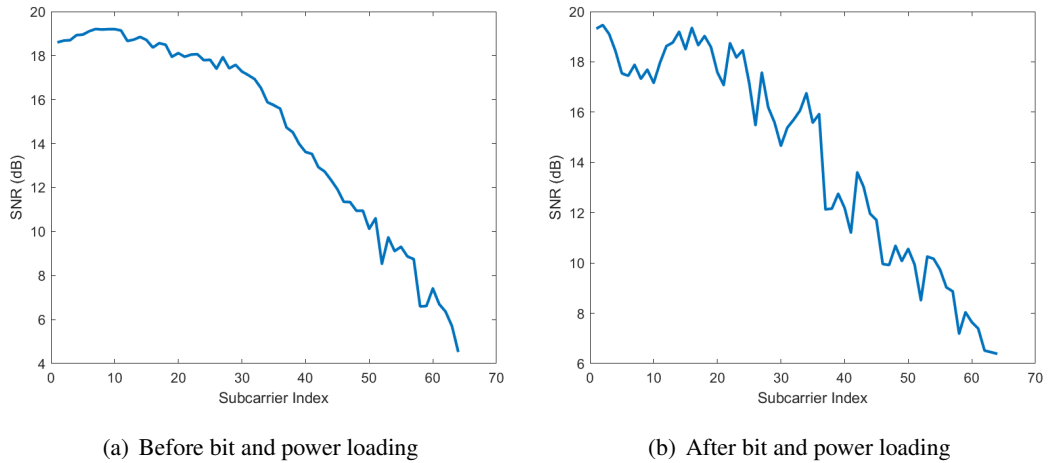


Figure 6.9: The SNR distribution for each subcarrier in tap water

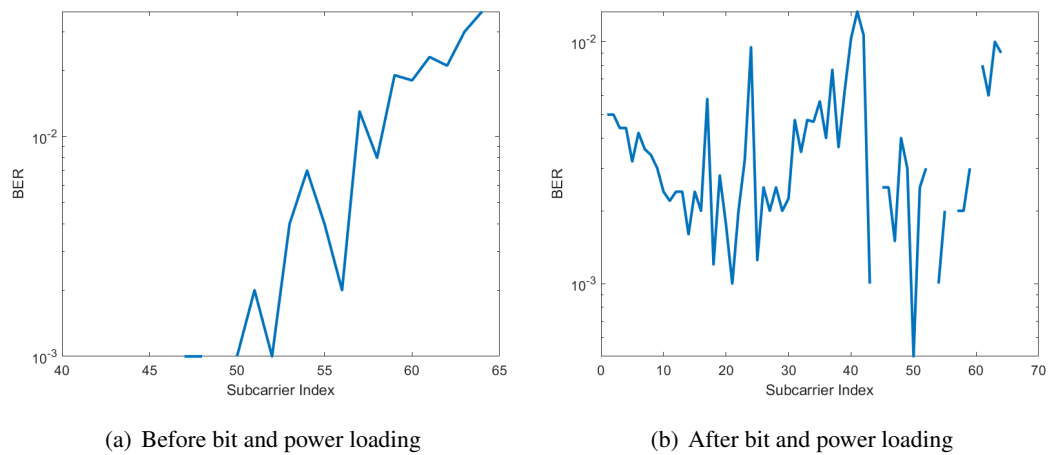


Figure 6.10: The BER performance for each subcarrier in turbid 1

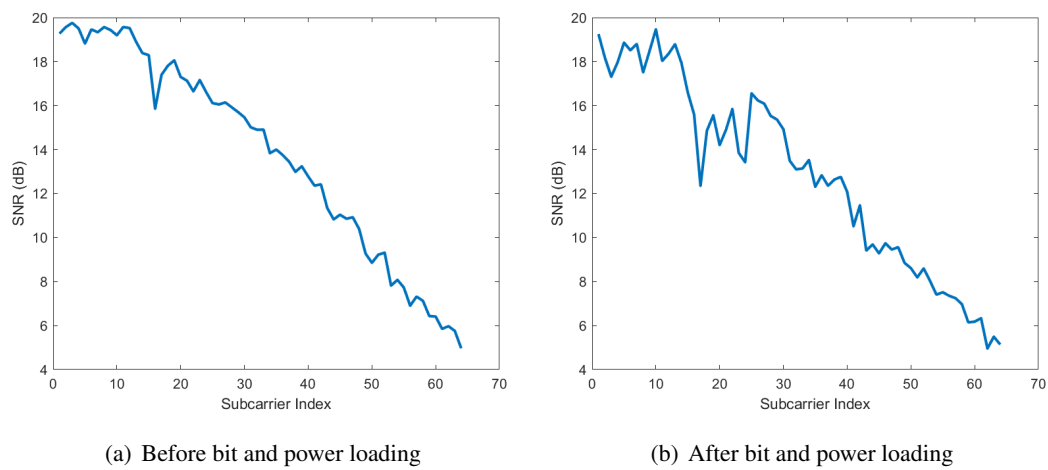


Figure 6.11: The SNR distribution for each subcarrier in turbid 1

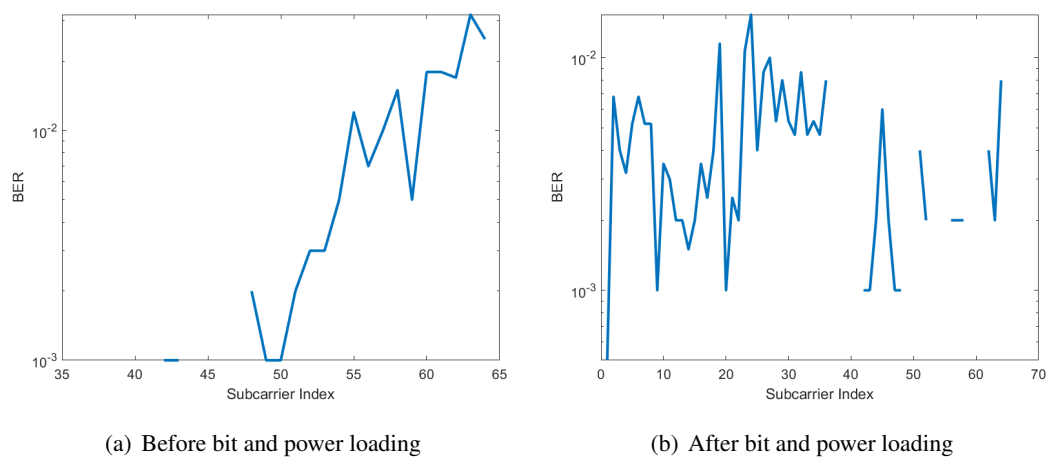


Figure 6.12: The BER performance for each subcarrier in turbid 2

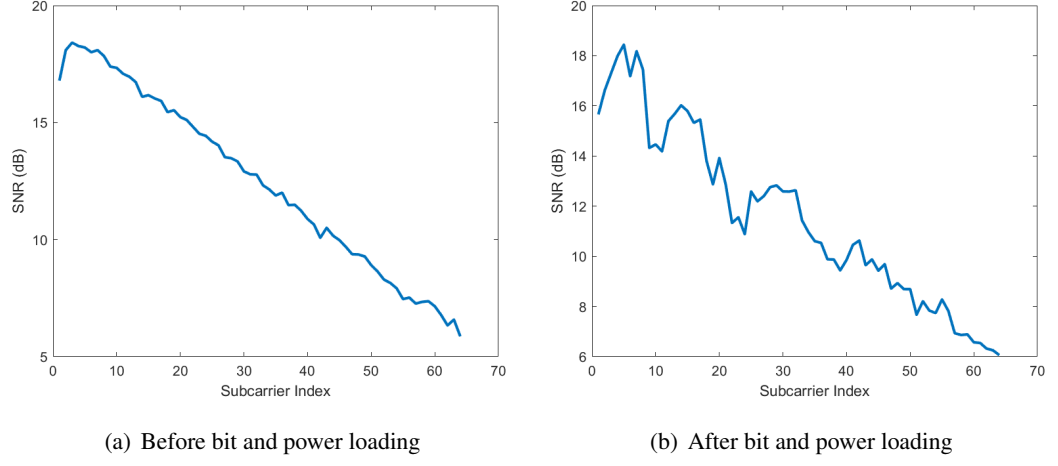


Figure 6.13: The SNR distribution for each subcarrier in turbid 2

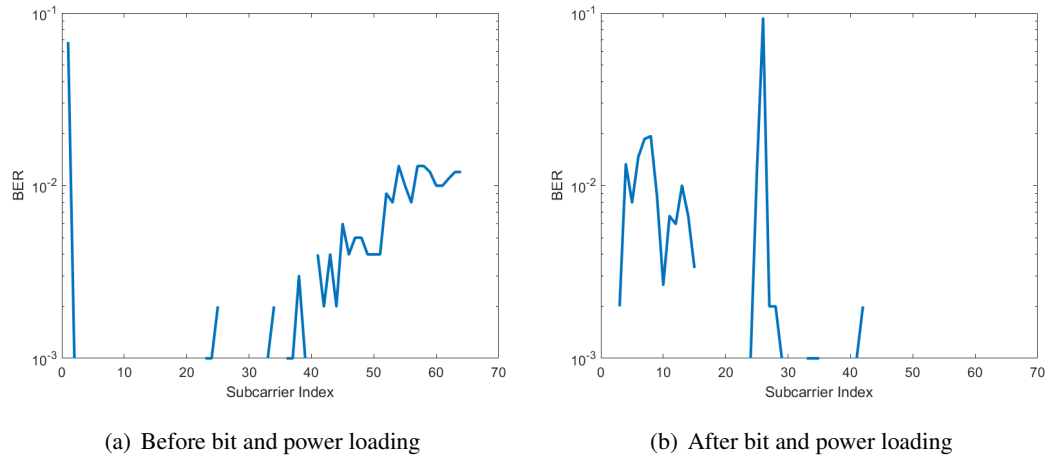


Figure 6.14: The BER performance for each subcarrier in turbid 3

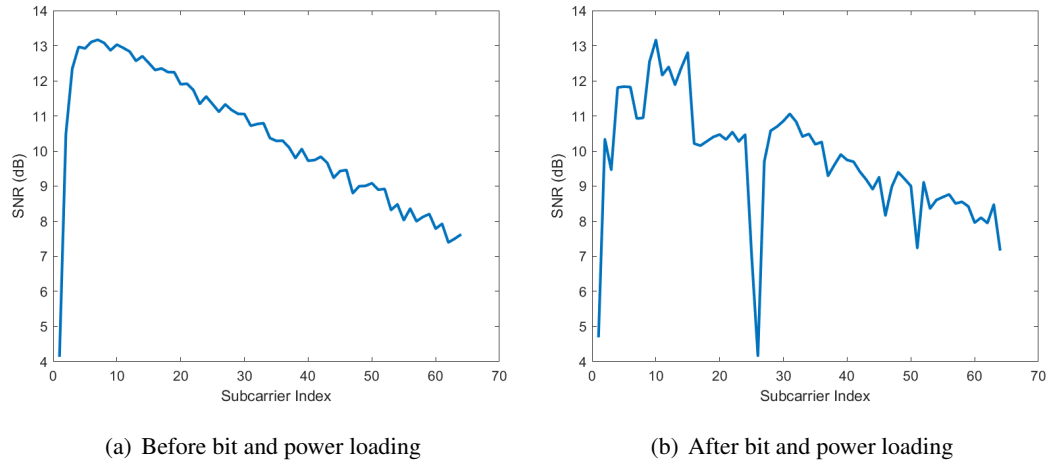


Figure 6.15: *The SNR distribution for each subcarrier in turbid 3*

6.5 Summary

In this chapter, the performance of CAP, QAM-OFDM and PAM in different water conditions was investigated experimentally. It was shown that for the same modulation, M , the performance of QAM-OFDM is better than CAP and PAM when c' is below 1.2 m^{-1} . This data rate could be further increased by applying the BPL technique to QAM-OFDM to achieve a maximum data rate of 557 Mbps in still water. CAP and PAM have very close transmission rates in various underwater channels, but 8-PAM cannot be supported below the FEC limit in the turbid 3 channel. In addition, in turbid 3, 64-CAP and 64-QAM-OFDM have the same performance but 16-CAP exceeds 16-QAM-OFDM. CAP and PAM have some tolerance to turbidity, but CAP has stronger tolerance than PAM. Although the performance of QAM-OFDM is generally better than that of CAP and PAM, it is most susceptible to the impact of turbidity and the maximum data rate achievable with QAM-OFDM decreases rapidly with an increase in c' .

Chapter 7

Conclusion

7.1 Summary

This thesis investigated three modulation schemes for use in UOWC systems namely PAM, CAP and QAM-OFDM. The UOWC system was evaluated through analytical study and experimental analysis in this study. Equalisation techniques were also investigated for use with the modulation techniques under test, they are DFE, VDFE, and ZFE. These equalisation techniques were required to overcome the limited bandwidth of the LEDs. The work presented the performance of the various modulation formats in 1.5 m emulated natural water condition links. The work concludes with experimental comparisons of modulation formats with their maximum data rate for UOWC systems with turbid water.

Chapter 1 demonstrates the background knowledge about underwater optical wireless communications. Also, the thesis objectives were defined, like the maximum transmission rate in the water condition satisfying the minimum target criteria. In chapter 2, the history of UOWC development over the past six decades has been presented, and the common source used in OWC is LD and LEDs employed with the IM/DD scheme for short-range optical communication systems. The advantage and disadvantages of both sources of water have been discussed for which one is suitable for seawater conditions. The advanced modulation used in this study is given the details about the principle and the implementation. In chapter 3, the characterisation of light propagation in the water was discussed. IOPs mainly are separated into absorption and scattering and the measurement scheme is introduced for the part of the further experiment. In chapter 4, equalisation techniques used to overcome the drawback of LEDs and channels to achieve a reliable communication system in this study include linear and nonlinear equalisers. They differ in their computational complexities, the DFE and ZFE are linear equalisers but ZFE is simpler than DFE. The Volterra DFE is highly complex than DFE to solve the impact of the nonlinearity of LEDs. In chapter 5, the characterisation of the LED-based UOWC is based on the experimental setup. The channel condition is controlled by an UCE and the attenuation coefficient is levelled against antacid concentration. The limited modulated bandwidth is

shown in the normalised frequency response of the system in a clear water link. Importantly, the average SNR in turbid water conditions presents the effects of turbidity on attenuating the optical power. In chapter 6, an empirical comparison of the performance of different modulation schemes in underwater channels is investigated. The 2nd-order VDFE have identical performance compared to DFE when the LED is working in the linear region of power to the current curve. If considering the condition without non-linear distortion, DFE is more suitable for CAP as the lower complexity. The maximum data rate is 577 Mbps for QAM-OFDM applying BPL in clear water, while in turbid water, CAP and PAM presented better tolerance against turbidity than QAM-OFDM. 16-CAP reached the maximum data rate at 113 Mbps under the FEC limit in turbid 3 which exceeds QAM-OFDM. While PAM is the simplest modulation scheme for OWC, it only can achieve 100 Mbps below the attenuation coefficient of turbid 2 ($c' < 0.8$).

7.2 Limitations and Future Direction

In this thesis, the use of equalisers with advanced modulation formats achieved > 100 Mbps level data rate in a range of water conditions. However, there are still some other techniques that can improve in terms of data rate. The first direction is the equalisation technologies, this work only considers the fast convergence to reduce the training length but it is not adaptive. Additionally, the equaliser can be considered to overcome the harsher underwater environments by increasing their complexity, such as higher-order VDFE or neural network equalisers [87, 88]. The second consideration is the variants of the advanced modulation formats used in this work that can achieve higher speeds, these variations combined with the further equaliser can achieve a higher transmission rate in an enhanced extinction water environment [89]. Additionally, WDM technology can improve the data rate by combining the modulated numerous data streams like various wavelengths (colours) of optical sources [14, 90, 91]. Meanwhile, multiple input multiple outputs (MIMO) can be utilized together to enhance the data rate performance [92]. Finally, this work aims to the implementation of real-time applications in the real-world ocean. Considering a cost-efficient real-time field programmable gate arrays (FPGA) on LED-based UOWC at Mbps domain is also feasible for future direction [34, 93].

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