Investigation of Jervol water types properties effects on underwater optical wireless OCDMA system performances for different modulation techniques

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Abstract
In this paper, an analytical evaluation of the direct detection OCDMA system is presented in an underwater wireless optical channel. Performances were evaluated by varying the main simulation parameters (range, transmitted power, number of users, and inclination angle) considering different modulation techniques for different water types (categorized according to Jerlov classification). It is found that the BER performance of this system significantly depends on the water type and the receiver’s position and that QAM modulation provides the best performance for the proposed system. The work is supplemented by a simulation implementation using the results thus obtained agree with those of the theoretical calculations.

Keywords UWOC · OCDMA · Optical modulations · Attenuation · Water type

1 Introduction
Underwater wireless optical communications (UWOC) has become the focus subject of many recent wireless communications studies Kaushal and Kaddoum (2016). Allowing high data rates, it represents the ideal candidate for underwater transmissions (compared to few kbits/s rates achievable by acoustic and radio-frequency (RF) underwater communications Chen et al. (2019); Khalighi et al. (2014); Saeed et al. (2019).

In optical oceanography, Jerlov categorized waters into oceanic and coastal types based on their chlorophyll concentration Solonenko and Mobley (2015) . The latter directly affects the water’s particles sizes and consequently the scattering and absorption effects on any light beam propagation underwater. The objective of this study is, considering these drawbacks, to translate the benefits of Optical Code Division Multiple Acces (OCDMA, more traditionally implemented in optical fibers systems) in UWOC systems.

This paper is organized as follows: In Sect. 2, the UWOC/OCDMA studied system is presented, followed by the channel properties in Sect. 3. Section 4 is devoted to the
theoretical bit error rate calculations considering different modulations schemes. To highlight the outcome from these calculations, the obtained results are compared to those of similar studies existing in the literature in Sect. 6. Finally, the studied system is implemented thru simulation analysis in Sect. 6. The performance is evaluated by referring to the BER and the constellation diagrams.

2 System description

The studied system is represented in Fig. 1. On the transmission side, each user’s spectral signature (defined by its respective ZCC code sequence) is the modulated user’s data (the different modulation techniques considered in this study are detailed later in this paper, see Sect. 4). It’s then diffused thru the water channel by optical lenses. The water’s inherent properties and particles will strongly affect the signal power. At the receiver, the direct detection (DD) technique is used. Introduced by Abdullah et al. (2008), it consists of the detection of only one of the spectral signature’s wavelengths Fig. 2 (since there is no overlap between the ZCC codes users). It allows a simpler system (compared to optical balanced detection conventionally used), and the low value of captured power at the receiver (because only one wavelength is detected) will allow us to test the system limitations.
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for the most critical case (the captured power is $\omega$ times smaller than the one studied in Al Hammadi and Islam (2020) and Yadav and Kumar (2020), $\omega$ being the code weight).

3 UWOC channel properties

Line of sight (LOS), link configuration, defines the path of communication between transmitter ($T_x$) and receiver ($R_x$), as shown in Fig. 3. In this scenario, ($T_x$) directs the light beam in the direction of ($R_x$), where the captured power (in the case of a LOS link of distance $d$) $P_{Rx}$ is defined as Ghassemlooy et al. (2019):

$$P_{Rx} = P_{Tx} \eta_{Tx} \eta_{Rx} \frac{A_{Reff} \cos(\varphi)}{2 \pi d^2 [1 - \cos (\varphi_0)]} \exp \left[-c(\lambda) \frac{d}{\cos(\varphi)}\right]$$

(1)

Where $P_{Tx}$ is the transmitted power, $\eta_{Tx}$ and $\eta_{Rx}$ are respectively the optical efficiency of the transmitter and the receiver, and $A_{Reff}$ is the effective aperture area of the receiver.

The captured power also depends on the transmission beam divergence angle $\varphi_0$ and the transmitter inclination angle $\varphi$. Those angles are illustrated in Fig. 3 for a LOS link configuration.

Another important parameter to take into consideration is the attenuation coefficient $c(\lambda)$. In UWOC it depends on the operating transmission wavelength. It’s also defined as the sum of absorption and scattering coefficient respectively represented by $a(\lambda)$ and $b(\lambda)$ Rashed and Sharshar (2013):

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

(2)

$a(\lambda)$ and $b(\lambda)$ are in function of the concentration of suspended and dissolved particles in the water Rashed and Sharshar (2013), both of which directly affect the light beam propagation. By referring to Jerlov water classification, the typical values of absorption, scattering, and extinction coefficients for different water types are listed in Table 1:

**Fig. 3** Beam divergence angle ($\varphi_0$) and transmitter inclination angle ($\varphi$) in LOS link
4 Theoretical study

4.1 BER calculation

The Signal to Noise Ratio (SNR) is defined, depending on the average signal power $i_k$ and average power of all noise sources $\sigma$, as:

$$\text{SNR} = \frac{i_k^2}{\sigma^2}$$  \hspace{1cm} (3)

The total variance of noise sources $\sigma^2$ is defined as the sum of shot noise variance ($\sigma_{sh}^2$) and thermal noise variance ($\sigma_{th}^2$). In the studied case, the phase-induced intensity noise (PIIN) is neglected to the ZCC codes properties (no spectral signatures overlapping between all active users). Hence, considering DD receiver (Fig. 2), $i_k$ and $\sigma$ can be expressed as (demonstration detailed in Garadi et al. (2017)):

$$i_k = \Re P_{sr} \frac{1}{L}$$  \hspace{1cm} (4)

and

$$\sigma^2 = 2eB_i_k + \frac{4k_b T_n B}{R_1} = 2eB\Re P_{sr} \frac{1}{L} + \frac{4k_b T_n B}{R_1}$$  \hspace{1cm} (5)

Where $\Re$ is the photodetectors responsivity, $B$ is the electrical bandwidth of the receiver, $T_n$ is the receiver noise temperature, $k_b$ is Boltzmann constant and $R_1$ Receiver load resistor Imtiaz et al. (2020), Garadi et al. (2017), Kandouci et al. (2017).

As shown in Fig. 2, a regular receiver (a) is based on the detection of all the power emitted by the desired user. Conversely, the direct detection technique (b) is based on the detection of a part of the power emitted by the desired user (The total power divided by length of the code), which makes the second simpler (because only one optical filter is required at the reception) thus creating a more cost-effective system.

The captured power at the receiver $P_{sr}$, in the case of UWOC channel, is equivalent to $P_{Rx}$. Including thus, all the constraints of the underwater channel. From Equations (1, 3, 4 and 5), the SNR of the studied system becomes:

$$\text{SNR} = \frac{\left(\Re \cdot P_{Tx} \eta_{Rx} \frac{A_{Riv} \cos(\varphi)}{2 \pi d^2 \left[1 - \cos(\varphi_0)\right]} \exp \left[-c(\lambda) \frac{d}{\cos(\varphi)}\right] \cdot \frac{1}{L}\right)^2}{2eB\Re \cdot P_{Tx} \eta_{Rx} \frac{A_{Riv} \cos(\varphi)}{2 \pi d^2 \left[1 - \cos(\varphi_0)\right]} \exp \left[-c(\lambda) \frac{d}{\cos(\varphi)}\right] \cdot \frac{1}{L} + \frac{4k_b T_n B}{R_1}}$$  \hspace{1cm} (6)

| Jerlov water type    | $a(m^{-1})$ | $b(m^{-1})$ | $c(m^{-1})$ |
|---------------------|-------------|-------------|-------------|
| Clear water         | 0.053       | 0.003       | 0.056       |
| Clear ocean         | 0.069       | 0.08        | 0.15        |
| Coastal ocean       | 0.088       | 0.216       | 0.305       |
| Turbid harbor       | 0.295       | 1.875       | 2.17        |

Table 1 Absorption, scattering and extinction coefficients for different water types (according to Jerlov classification)
To investigate the OCDMA-UWOC studied system performances, it is necessary to evaluate the Bit Error Rate (BER). The relationship between the latter and the SNR depends closely on the modulation scheme chosen Akter et al. (2020). Various modulation techniques are used in communications systems due to their bandwidth efficiency, ease of implementation, and cost-effectiveness. The ones considered in this study are non-return to zero on-off keying (NRZ-OOK), return to zero on-off keying (RZ-OOK), and Quadrature amplitude modulation (QAM).

BER can be expressed, by estimation from SNR, for different modulation schemes as follows Ali (2020) :

- for RZ-OOK Ali et al. (2020):

\[
BER_{\text{RZ-OOK}} = \frac{1}{2} \text{erfc} \left[ \frac{1}{2} \sqrt{\frac{\text{SNR}}{2}} \right]
\]  

(7)

- for NRZ-OOK Zou Wei et al. (2001)

\[
BER_{\text{NRZ-OOK}} = \frac{1}{2} \text{erfc} \left[ \frac{1}{2} \sqrt{2 \sqrt{\frac{\text{SNR}}{2}}} \right]
\]  

(8)

- for M-QAM Mesleh et al. (2011):

\[
BER_{M-QAM} = \frac{\sqrt{m-1}}{\sqrt{m \log_2 m}} \text{erfc} \left[ \sqrt{\frac{3\text{SNR}}{2\left(m-1\right)}} \right]
\]  

(9)

Where \( M \) represents the level of the QAM.

### 4.2 Results and discussion

In this section, the BER investigation of DD-OCDMA UWOC is presented for various modulation schemes (cited in Sect. 4). The considered parameters are displayed in Table 2, considering a constant depth and no water turbulence.

| Table 2  | BER calculation parameters |
|----------|----------------------------|
| Operating parameter | Value |
| Operating wavelength | 575 nm |
| Transmitter efficiency \( \eta_{Tx} \) | 0.8 |
| Receiver efficiency \( \eta_{Rx} \) | 0.8 |
| Data bit rate | 1 Gbit/s |
| Responsivity \( (Re) \) | 0.6 (A/W) |
| Boltzmann constant \( (k_b) \) | 1.38 \(10^{23} (JK)\) |
| Temperature \( (T_n) \) | 298 (K) |
| Load resistance \( (R_l) \) | 1 KΩ |
| Transmission distance \( (d) \) | 10 m |
| Transmitted power | 500 mW |
| Effective aperture area of the receiver | 0.01m² |
| Beam divergence angle \( (\phi_o) \) | 60° |
| Transmitter inclination angle \( (\phi) \) | 5° |
Figure 4 illustrates the bit error rate variation in function of the number of active users considering a transmission power of 500 mW and a code weight $\omega = 3$ for a 5 m transmission distance (in clear water). It shows that the suitable $10^{-9}$ BER is achievable for 12 active users using NRZ-OOK modulation, around 15 active users using RZ-OOK and 64-QAM modulation, and up to 22 users using 16-QAM, making it the more suitable modulation format for the studied scheme.

In Fig. 5, the same previous parameters are considered for different water types. In the case of a clear ocean, the suitable BER is only reachable for less than 10 users and non-achievable for a coastal ocean (due to the low value of the transmission power). Turbid water was not discussed in this study do its high attenuation factor (as shown in Table 1).

It is demonstrated in Fig. 6 that the system performance and the increase in transmitted power have a direct positive correlation (which is translated by a decrease in the BER value). Indeed, according to the water type and the spread of its impurities, more power could be needed to overcome the optical attenuation induced by the channel.

Also studied is the range effect by varying the transmission distance for different water types when the number of simultaneous users is 5 and transmitted power is 500 mW (see Fig 7. As in the previous cases, the BER depends strongly on the chosen water type. The maximum ranges with acceptable BER can be reached for clear water (26 m). 16-QAM also proved to be the more efficient modulation scheme. For other water types, the acceptable system performance can only be achievable for a range not exceeding 10 m in the coastal ocean and 15 m for the clear ocean.

In Fig. 8, the transmitter inclination angle ($\varphi$) is varying from $0^\circ$ to $90^\circ$, for a $60^\circ$ beam divergence angle ($\varphi_0$). $\varphi$, as shown previously Fig. 3, is defined by an angular value characterizing the deviation between the axis connecting the transmitter-receiver and the source’s optical beam trajectory. Therefore, as reflected in Fig. 8, the system performance declines as the source beam aligns away from the axis connecting the transmitter and the receiver.

The obtained results are in agreement with existing OCDMA-UWOC works in the literature Al Hammadi and Islam (2020) Yadav and Kumar (2020) with a simpler detection
Fig. 5  BER versus number of users for clear and coastal ocean

Fig. 6  BER versus transmitted power
Fig. 7 BER versus transmission distance

Fig. 8 BER versus transmitter inclination angle
scheme and a significantly smaller captured power at the receiver. This is due to the ZCC codes properties. 16-QAM modulation was also determined to be the most effective in this study case.

5 Comparison to related studies

Similar theoretical studies on OCDMA-UWOC channels has been done by Ali (2015) using Optical Orthogonal Codes (OOC) and Yadav and Kumar (2020) using a two dimensional one-coincidence frequency hopping code/quadratic congruence codes (2D-OCFHC/QCC). Table 3 highlights the advantages of the proposed system compared to the existing ones.

6 Simulation analysis

6.1 OCDMA implementation

For a 4 active users system with spectral length $L = 13$ and temporal length $p = w = 3$, according to Kandouci et al. (2017) construction and ideal transmission wavelength for different water types (defined by Kaushal and Kaddoum (2016)) each user’s respective spectral signature is defined in Table 3 for 100 Ghz (0.8 nm) chip spacing.

Unlike fiber-optic communications, where the spectrum is centered around 1550 nm, in UWOC the range of 450–550 nm wavelengths (blue and green lights) is considered to minimize the signal attenuation in clear water Table 4.

6.2 Simulation setup

The studied simulation setup using Optisystem V.17 software is presented in Fig. 9.

Table 3 Comparison to related studies

| Study                        | Optical code family | Modulation  | Water type      | Max. Range (m) | Max. Cardinality |
|------------------------------|---------------------|-------------|-----------------|----------------|------------------|
| Al Hammadi and Islam (2020) | OOC                 | NRZ-OOK     | Clear water     | 27.9           | 8                |
|                              |                     |             | Clear ocean     | 16             | 2                |
|                              |                     |             | Coastal ocean   | 8              |                  |
| Yadav and Kumar (2020)       | 2D-OFHC/QCC         | NRZ-OOK     | Clear water     | 20             | 7                |
|                              |                     |             | Clear ocean     | 20             | 7                |
|                              |                     |             | Coastal ocean   | /              | /                |
| Proposed system              | ZCC                 | 16-QAM      | Clear water     | 26             | 21               |
|                              |                     |             | Clear ocean     | 15             | 7                |
|                              |                     |             | Coastal ocean   | 8              |                  |
At the transmitter, the continuous wave (CW) laser array generates the spectral signature corresponding to each user’s code word (user 1 in this example). This light is then split into X and Y polarizations to work as optical carriers for the in-phase and quadrature (I/Q) based optical 16-QAM modulators. The polarization combiner combines the X and Y polarized modulated optical signals and produced the 16-QAM signal. In each 16-QAM transmitter structure (Fig. 10), the modulator consists of M-ary pulse generators, dual-drive Mach-Zehnder modulators (MZM), and one 90-degree phase-shifter. The second branch optical signal has a relative phase shift of 90-degree. Thus generating e the 16-QAM modulated optical signal at the cross coupler output. The QAM sequence generator does the mapping of the incoming bit sequence into 16-QAM symbols (of 4 bits each).

![Simulation setup](image)

**Table 4** Wavelengths assignation

| Water type  | Operating wavelength | Spectral signatures                        |
|-------------|----------------------|--------------------------------------------|
| Clear water | [450–500 nm] Blue/Green | User1: \(\lambda_1=450.4\text{nm};\lambda_3=460\text{nm};\lambda_9=464.8\text{nm}\)  
User2: \(\lambda_5=451.2\text{nm};\lambda_6=462.4\text{nm};\lambda_7=461.6\text{nm}\)  
User3: \(\lambda_4=460.8\text{nm};\lambda_12=467.2\text{nm};\lambda_{10}=465.6\text{nm}\)  
User4: \(\lambda_8=464\text{nm};\lambda_{11}=466.4\text{nm};\lambda_7=463.2\text{nm}\) |
After the signal has passed through the UWOC channel (having the properties presented above in this section), a single wavelength from the desired user’s spectral signature is detected by a Gaussian optical filter, thus eliminating signals from interfering users. At the QAM receiver (Fig. 11), the homodyne detection scheme is implemented. It consists of (24) 90-degree optical hybrid followed by balanced photodetectors and electronic amplifiers. Intensity fluctuations in the two branches are perfectly correlated and cancel out during the subtraction of the two photocurrents.

In order to simulate the UWOC environment as close as possible, the following typical industry values are considered as additional losses: (Li et al. (2021), Cox and Muth (2014)):

- Propagation delay = 1500 m/s ;
- Optical loss through the glass = 0.35 dB ;
- Reflection loss lens’s mirrors = 0.65 dB ;
- Attenuation in clear water = 0.39 dB/m.
6.3 Results

Figure 12 shows the simulated BER performance of OCDMA implementation in UWOC for both NRZ and 16-QAM modulations.

Using the electrical constellation visualizer, in Fig. 12 constellation diagrams for range values of 9 m, 24 m, 25m, and 26 m, respectively. Parameters such as bit rate, transmitted power, Beam divergence angle, etc. are considered as shown in Table 2. It is observed that between 9m and 24m the constellation points become less distinct. However, the acceptable BER is still achievable. Thereby, the overlapping constellation points across the link distance boundary (24m) produces an unacceptable BER.

7 Conclusion

In this paper, the UWOC-OCDMA system performances limitations were evaluated by referring to the bit error rate. To optimize the results, 4 different modulations techniques were considered (RZ-OOK, NRZ-OOK, 16-QAM, and 64-QAM). The constraints considered in this study were the optical attenuation due to water particles and the detection of the lower acceptable power to reconstitute each user’s data. Acceptable BER was achievable for the highest link distance of 26m.

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Declarations

Conflict of interest  The author declared that they have no conflict of interest.

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