Bio-Optical Modelling – Phytoplankton Absorption in ocean water

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Abstract-- The nature of received signal when a PPM/OOK modulated signal passes through a channel characterized in terms of OAS for underwater environment. Optical signal of blue-green wavelength is greatly attenuated by the optically active substances (OAS) in water. The OAS considered here is the phytoplankton's since they tend to absorb the blue-green wavelength the most. To determine the specific absorption co-efficient of various species of phytoplankton, with different Photo synthetically Absorptive Radiation (PAR) two component model is used. Further performance metrics like Signal to Interference ratio (SIR) and Bit Error Rate (BER) for PPM and OOK modulation schemes are studied and compared. This is applied to the data's of Bay of Ville franche - France (Mediterranean sea), Kaduviyar estuary - Nagapattinam, Tamil Nadu in India and Palk Bay, south east coast of India.

Keywords-- Optically Active Substances (OAS), Photo synthetically Absorptive Radiation (PAR), Signal to Interference Ratio (SIR), Bit Error Rate (BER).

I. Introduction

Optical methods are well posed to provide an alternative solution for high bandwidth communications in undersea compared to the traditional acoustic links. The most common optical communications modulation scheme used for free space optical link is on-off key (OOK) and this modulation method has been usually adopted in underwater wireless optical link due to its simplicity in system implementation. Pulse Position Modulation (PPM) also sometimes known as pulse-phase modulation is a system in which the amplitude and width of the pulse is kept constant (L ,the number of levels).The position of each pulse, in relation to the position of a recurrent reference pulse, is varied by each instantaneous sampled value of the modulating wave. This is often used in optical communication, such as fiber optics, in which there is little multipath way interference.

While On-off keying (OOK) the simplest form of amplitude-shift keying (ASK) modulation that represents digital data as the presence or absence of a carrier wave. The OAS acts as a hindrance for the proper transmission of optical signal, in underwater wireless optical communication. This led to the need for developing bio optical model, which is inevitable to determine the channel efficiency. Here the channel refers to the water medium. The nature of the water medium varies from one scenario to another in the aspect of salinity, density, biomass concentration as well as the depth at which the transceiver is placed under the water. Further, this model serves as an optical tool to explore the concentration of phytoplankton in open ocean, which is the direct measure of pollution.

II. Materials and Methodology

A. Literature Survey

Various models are available for retrieval of the absorption due to the phytoplanktons, including [4] inverse analytical model, which involves mapping spatial distribution from satellite imagery from the Sea WIFS and Modis Aqua data. But the non-linear relationship between satellite radiance image data and concentration makes this mode of retrieval poor in accuracy. In [5] Matrix inversion approach exploits the linear summability of IOPs (Inherent Optical Properties) and is based on reflectance R at specific wavelength. IOPs are those properties which depend only upon the medium and independent of the ambient light field. There exist AOPs (Apparent Optical Properties) which depend on both the medium and the structure of the ambient light field. On the other hand it employs grid search over unknown parameters which is exhaustive. Another technique [6] combines an analytical bio-optical model with statistical modelling for the formulation of posterior probabililty distributions of phytoplankton absorption, backscattering, and colored dissolved organic matter (CDOM) absorption. The performance of different modulation schemes for underwater optical wireless communication with marine bio-optical model are analyzed which suggested that for underwater application, it is required to trade off the water property and wavelength to improve the communication efficiency [11].

B. Two-Component Model

This model relates the absorption coefficient of phytoplankton to chlorophyll-a concentration. The total absorption coefficient 'a' of the given substance at a given wavelength 'λ',

$$a(\lambda) = \mathrm{C}a^*(\lambda) \qquad (1)$$

where, a*(λ)=specific absorption coefficient
C = sum of concentrations of chlorophyll-a.

The total chlorophyll-a Concentration(C) is the sum of the concentrations C_1 and C_2 of two phytoplankton populations 1 and 2 with distinct optical characteristics, such that

$$C = C_1 + C_2 \qquad (2)$$

The optical properties of natural phytoplankton can be described by combining the optical properties of any two populations in varying proportions. Assuming that C_1 is the dominant component of the phytoplankton population at low chlorophyll-a concentration, and that this population does not increase to concentrations greater than some threshold value beyond which the second population becomes dominant. The following equation shows the change in C_1 in terms of total chlorophyll-a concentration C,

$$C_1 = C_{1(\max)}[1 - \exp(-SC)]$$

(3)

where, S is the initial slope which determines the rate at which C_1 increases with increase in C and the concentration C_1 reaches a maximum value of $C_{1\,(\max)}$. By the additive property of the phytoplankton absorption coefficient,

$$a_p(\lambda) = a_1^*(\lambda)C + a_2^*(\lambda) \qquad (4)$$

where, $a_p(\lambda)$=total absorption coefficient due to phytoplankton at wavelength λ,

$a_1^*(\lambda)$, $a_2^*(\lambda)$ = specific absorption coefficients of populations 1& 2 at λ.

Combining (3) with (1) and (2),

$$a_p(\lambda) = X[1 - \exp(-SC)] + a_2^*(\lambda)C$$

(5)

$$X = C_1^m[a_1^*(\lambda) - a_2^*(\lambda)]$$

(6)

where, X = an unknown parameter.

The parameters X, S and $a_2^*(\lambda)$ are treated as unknown parameters when (5) is fitted by the least square method to data on phytoplankton absorption and chlorophyll-a concentration. Once the bio-optical properties of the two populations are determined, any concentration C of chlorophyll-a in the medium can be expressed as the sum of concentrations C_1 and C_2, along a continuum from C→ C_1 at low concentrations to C→C_2 at high concentrations.

Once we know *$a_1^*(\lambda)$*, the value of C_1^m can be obtained from (5) since $a_2^*(\lambda)$ is already known from fitting (6) to the data. Thus, by applying a single, simple and realistic assumption on the dominant phytoplankton population at low concentrations (i.e., C_2→0 when C→0), the model of Sathyendranath et al. [2001] can be used to obtain information on the spectral absorption characteristics of the two dominant phytoplankton populations as well as on the asymptotic maximum concentrations attained by the population 1.

III. Implementation Of Two Component Model

Once the OOK/PPM modulated signal is generated at the transmitter end, it passes through the bio optical model – here two component model (1). This characterizes the channel in terms of absorption.

Absorption of the water is given by the general equation,

$$a_p = (4 * pi * n) / PAR$$

(7)

where, n=refractive index(1.2 for Mediterranean sea)
PAR=Photosynthetically Available Radiation.

1. Austin Petzold's empirical relation

Further, the absorption coefficient for other wavelengths can be found using the Austin Petzold's equation. From the study of the spectral nature of the diffuse attenuation coefficient of light [8], attenuation properties were calculated over 365 to 700 nm and for depths from near-surface to in excess of 100 m. Examining the data, the following relation is obtained,

$$K(\lambda) = [K(\lambda_0) - K_w(\lambda_0)] + K_w(\lambda)$$

(8)

where, K_w=attenuation coefficient for pure sea water,
K=attenuation coefficient due to OAS and
λ_0 = operating wavelength.

Further,

$$K(\lambda) = ap(\lambda) + b(\lambda)$$

(9)

where, ap(λ) = absorption coefficient and
b(λ) = scattering coefficient.

Considering absorption alone,

$$ap(\lambda) = [ap(\lambda_0) - ap_w(\lambda_0)] + ap_w(\lambda)$$

(10)

2. Scenario 1 – Bay Of Villefranche, France Located In Mediterranean Sea[8]:

Abundance and composition of microplankton were studied in Villefranche Bay (Ligurian Sea, NW Mediterranean Sea). Diatoms dominated the microplankton in late spring and autumn, whereas dinoflagellates composed the major part of the microplankton in summer. The silicoflagellate dictyocha fibula and the diatom thalassionema frauenfeldii dominated in winter. The spring bloom was mainly composed of dinoflagellates near the surface and of diatoms in deeper layers. Dinoflagellates and tintinnids showed maxima in early November.

3. Scenario 2 -- Kaduviyar estuary[6]:

The results of an investigation carried out on composition of phytoplankton including chlorophyll 'a' (Chl-a) content at the

Kaduviyar estuary (Southeast coast of India) are reported. The ranges of Chlorophyll 'a' (mg m-3) values were: 3.4-12.8. Presently, 85 phytoplankton species representing different classes viz: Bacillariophyceae-58,Dinophyceae-16,Cyanophyceae-7,Chlorophyceae-3and Chrysophyceae-1 were recorded. Results have been posted in tables by applying two component model for different wavelength ranging from 450nm – 570nm for 8 different species. This shows that there is a gradual increase in the values as the wavelength increases.

The graphs have been plotted for different wavelengths of varying size of different species with respect to specific absorption coefficient in Fig.1. This shows that certain species offer higher absorption whereas some of them offer lesser absorption. The Plots shown in figures 2 and 3 are plotted by applying OOK and PPM modulation in the transmitter side.

4. Scenario 3: Palk Bay, southeast coast of India[12]

Spatial and temporal behavior of distribution of phytoplankton of the coral reef and sea grass environment of the Palk Bay was studied. A total of 133 species of phytoplankton was recorded during the study period, of which, 98 species belong to Bacillariophyceae, 15 species belong to Dinophyceae, 12 species belong to Cyanophyceae and 8 species belong to Chlorophyceae. Diatoms (57.14 to 94.10%) contributed more towards the percentage composition of different groups of phytoplankton, followed by dinoflagellates (3.12 to 28.57%), blue-greens (2.43 to 12.5%) and greens (3.7 to 7.69%).

TABLE 1a

RESULTS OF APPLICATION OF TWO COMPONENT MODEL IN SCENARIO 2

C (mg/m^3)	Species Name	Dia d(μm)	450 nm	460 nm	470 nm	480 nm	490 nm	500 nm
384	Hymenomonas elongata	13.5	13.2826	13.2837	13.2837	13.2857	13.2877	13.2938
225	Dunaliella marina	8.5	13.2372	13.2383	13.2383	13.2403	13.2423	13.2484
138	Platymonas suecica	5.8	13.5859	13.5870	13.5870	13.5890	13.5910	13.5971
247	Hymenomonas elongata	13.4	12.8236	12.8247	12.8247	12.8267	12.8287	12.8348
245	Platymonas suecica	5.6	6.3710	6.3721	6.3721	6.3741	6.3761	6.3822
467	Tetraselmis maculate	8.5	6.7221	6.7232	6.7232	6.7252	6.7272	6.7333
356	Chaetoceros Protuberans	14.4	7.1059	7.1070	7.1070	7.1090	7.1110	7.1171
781	Hymenomonas elongata	14	7.4023	7.4034	7.4034	7.4054	7.4074	7.4135

TABLE 1b

RESULTS OF APPLICATION OF TWO COMPONENT MODEL IN SCENARIO 2

C (mg/m^3)	Species Name	Dia d(μm)	510 nm	520 nm	530 nm	540 nm	550 nm	560 nm	570 nm
384	Hymenomonas elongata	13.5	13.3032	13.3158	13.3188	13.3239	13.3319	13.3389	13.3480
225	Dunaliella marina	8.5	13.2578	13.2704	13.2734	13.2785	13.2865	13.2935	13.3026
138	Platymonas suecica	5.8	13.6065	13.6191	13.6221	13.6272	13.6352	13.6422	13.6513

247	Hymenomonas elongata	13.4	12.8442	12.8568	12.8598	12.8649	12.8729	12.8799	12.8890
245	Platymonas suecica	5.6	6.3916	6.4042	6.4072	6.4123	6.4203	6.4273	6.4364
467	Tetraselmis maculate	8.5	6.7427	6.7553	6.7583	6.7634	6.7714	6.7784	6.7875
356	Chaetoceros Protuberans	14.4	7.1265	7.1391	7.1421	7.1472	7.1552	7.1622	7.1713
781	Hymenomonas elongata	14	7.4229	7.4355	7.4385	7.4436	7.4576	7.4586	7.4677

TABLE 2: RESULTS OF APPLYING MODULATION TECHNIQUES

Wave length (nm)	SCENARIO I					SCENARIO II					SCENARIO III				
	Attenua-tion K (dB/m)	SIR(dB)		BER(x 10^{-9})		Attenua--tion K (dB/m)	SIR(dB)		BER(x 10^{-9})		Attenu-ation K (dB/m)	SIR(dB)		BER(x 10^{-9})	
		OOK	PPM	OOK	PPM		OOK	PPM	OOK	PPM		OOK	PPM	OOK	PPM
450	48.1098	14.8387	13.5722	1.145	1.017	48.4092	14.8279	13.5598	1.146	1.017	47.2520	14.8740	13.6082	1.142	1.016
460	48.1103	14.8386	13.5722	1.145	1.017	48.4097	14.8278	13.5598	1.146	1.017	47.2525	14.8740	13.6082	1.142	1.016
470	48.1057	14.8388	13.5724	1.145	1.017	48.4052	14.8280	13.5600	1.146	1.017	47.2480	14.8742	13.6084	1.142	1.016
480	48.1109	14.8386	13.5722	1.145	1.017	48.4103	14.8278	13.5598	1.146	1.017	47.2532	14.8740	13.6082	1.142	1.016
490	48.1162	14.8385	13.5720	1.145	1.017	48.4157	14.8271	13.5596	1.146	1.017	47.2585	14.8738	13.6079	1.142	1.016
500	48.1413	14.8377	13.5709	1.145	1.017	48.4407	14.8269	13.5585	1.146	1.017	47.2792	14.8732	13.6071	1.143	1.016
510	48.1822	14.8364	13.5692	1.145	1.017	48.4813	14.8256	13.5568	1.146	1.017	47.3256	14.8717	13.6051	1.143	1.016
520	48.2385	14.8347	13.5669	1.145	1.017	48.5319	14.8239	13.5545	1.146	1.017	47.3766	14.8701	13.6029	1.143	1.016
530	48.2492	14.8343	13.5664	1.145	1.017	48.5468	14.8236	13.5541	1.146	1.017	47.3915	14.8696	13.6023	1.143	1.016
540	48.2700	14.8337	13.5656	1. 146	1.017	48.5695	14.8229	13.5532	1. 146	1.017	47.4123	14.8689	13.6014	1.143	1.016
550	48.3084	14.8325	13.5640	1. 146	1.017	48.6042	14.8218	13.5518	1. 146	1.017	47.4471	14.8678	13.6000	1.143	1.016
560	48.3350	14.8317	13.5629	1.146	1.017	48.6344	14.8209	13.5505	1.146	1.017	47.4772	14.8669	13.5987	1.143	1.016
570	48.3752	14.8304	13.5612	1.146	1.017	48.6746	14.9197	13.5489	1.147	1.017	47.5175	14.8656	13.5970	1.143	1.016

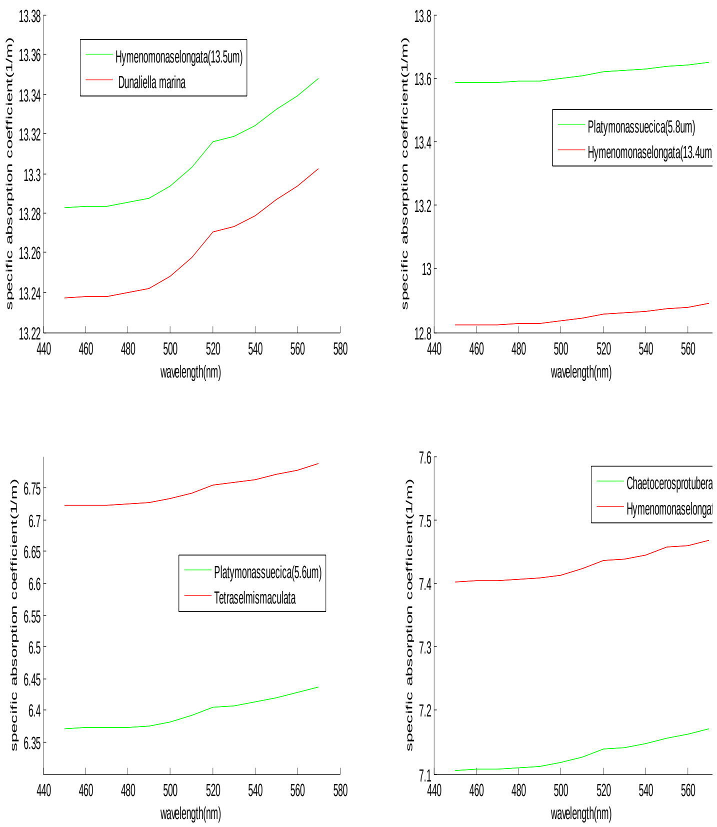

Fig.1.Simulation results of application of two component model in scenario 2

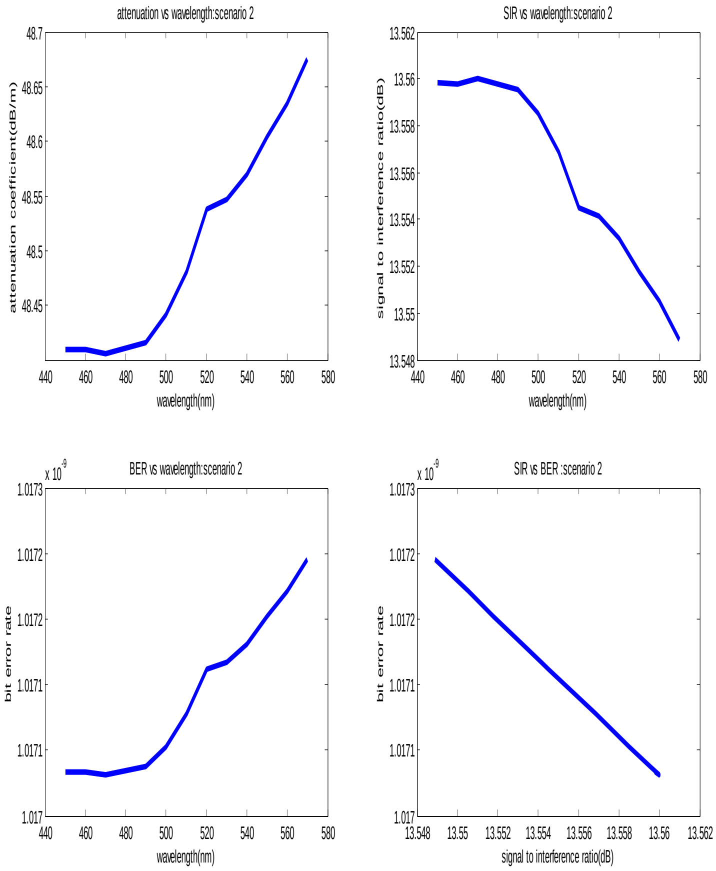

Fig. 3. Simulation results of applying PPM in scenario 2

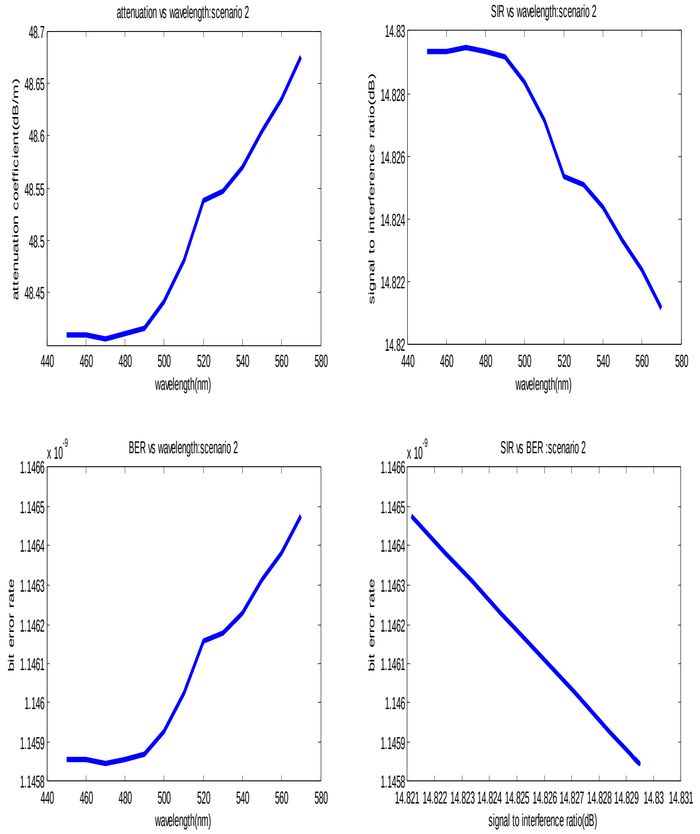

Fig. 2. Simulation results of applying OOK in scenario 2

IV. Conclusion

The application of the two component model gives the specific absorption coefficient at various blue-green wavelengths. Taking 8 different dominating species each with varying cell size and concentration, the specific absorption coefficient is found. It can be found from Fig. 4, 7, 10 that absorption by the phytoplankton increases with increase in wavelength making the lower limit of the blue-green wavelength suitable for better communication. Further, proceeding to the evaluation of the performance of the two modulation techniques 2-PPM, OOK shows that PPM has lower Bit Error Rate (BER) and lower Signal to Interference Ratio (SIR) than OOK. Then, SIR is higher and BER is lower for the lower limit of the blue-green wavelength for both the modulation techniques.

In future this can be extended by exploring the possibility of multiple scattering and back scattering in these scenarios. Also this can be combined with further exploitation of applying other modulation techniques.

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