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An Efficient Channel Modeling for Underwater Wireless Optical Communication Links

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***Abstract*---- Recently, the role of underwater wireless optical communication is increased considerably for underwater observation and sea monitoring. This communication technology has many applications like prediction of natural calamities, studying the climate changes, detection off natural resources etc. In underwater wireless optical communication (UWOC), multiple scattering may cause temporal spread of beam pulse, which is characterized by its impulse response. The temporal spread leads to inter-symbol interference (ISI) and degrades the system performance. In this paper, the optical characteristic of seawater is analyzed and some new parameters for accelerating the convergence speed and probability of mutant for maximizing the coverage rate are introduced. The bit-error-rate (BER) and bandwidth of the channel are further studied for various link ranges. The zero-forcing (ZF) equalization has been adopted to overcome ISI and improve the system performance. Harmony search Algorithm is proposed to model the channel impulse response and quantify the channel time dispersion under different conditions of water type, link distance, and the transmitter/receiver parameters. Comparing with the existing method, the proposed approach can achieve a better performance in coverage rate and convergence speed. HSA is used to optimize the phase shift parameters and to improve both the network connectivity and the harmonic phases. It is plausible and convenient to utilize this impulse response model for performance analysis and system design of UWOC systems.**

I. INTRODUCTION

Underwater acoustic communications which utilizes acoustic waves to transmit information has been widely studied and implemented in the past decades. However, the channel bandwidth of underwater acoustic links is typically limited to kHz since the sound is decayed in the ocean proportionally to its frequency. And the lower propagation speed typically 1500 m/s leads to a large time delay for acoustic system. Meanwhile, the multipath reflection of sound may cause signal fading and security issues. UWOC systems can provide high security, low time delay and a much higher data rate up to hundreds of Mbps in relatively short ranges (typically shorter than 100 meters). In this paper, focuses is mainly on the temporal dispersion of UWOC links and investigate the effect of corresponding impulse response. There are lots of theoretical and practical studies have been done on the impulse responses of underwater optical links. Most of the prior works are used Monte Carlo approach to model the impulse response of UWOC channels and validated the Monte Carlo approach of modeling the UWOC impulse response by experimental measurement. However, to the best of our knowledge, these prior works have not provided simple closed-form expressions of impulse response of UWOC links. In this paper, focus is mainly on the impulse response of relatively turbid water types such as harbor water where the temporal dispersion cannot be ignored and will affect the system performance. The double Gamma functions has been firstly adopted in modeling the impulse response of FSO links through fog and then applied to model the impulse response in dispersive medium characterized by Henyey-Greenstein (HG) function in earlier work .Although seawater has different properties from the medium studied in the prior works, they are dispersive medium through which the light may suffer the effect of multiple scattering. The optical properties of the seawater is analyzed by (a) apply the double Gamma functions to model the impulse response of UWOC links which fits well with the Monte Carlo simulation results (b) investigate the valid region of this model. Then, based on the double Gamma functions model, study the system performance of inter-symbol interference (ISI), bandwidth of the channel and the bit-error-rate (BER). The results got suggested that the temporal pulse spread reduce the BER performance without equalization based on on-off keying (OOK) modulation for high data rate and long. To eliminate the detrimental effect of ISI and improve the BER performance, equalization has been employed in atmospheric FSO links and indoor infrared links. In this paper, the simplest and most widely used zero-forcing (ZF) equalization based on double Gamma functions model is done to enhance the error performance of the high speed UWOC system operating in seawater environment in the presence of ISI.

II. LINK CHARACTERISTICS AND SYSTEM MODEL

1. Optical Characterization of Seawater

The interactions between seawater and each photon undergo absorption and scattering in beam propagation. In absorption process photons lose energy in the form of heat when it interacts with water molecules and other particles. In scattering, the direction of transmission of photons will be changed by the interactions between photons and seawater, which lead to energy loss because number of photons that reaches the receiver will be reduced. The loss in energy by absorption and scattering can be evaluated by absorption coefficient $a(\lambda)$ and scattering coefficient $b(\lambda)$, respectively. The attenuation coefficient is $c(\lambda) = a(\lambda) + b(\lambda)$ describes the total effects of absorption and scattering on photon energy loss. The values of $a(\lambda)$, $b(\lambda)$ and $c(\lambda)$ are different for different type of water and different source wavelength λ.

The UWOC links have a large number of suspended particles such as water dissolved salts, organic particles and mineral material compounds in underwater channels. In seawater of coastal area comparing to other areas the scattering of light is very high. There are three types of scattering happens in water. (a) scattering caused by density fluctuations (due to random molecular motions) (b) Particle scattering by big suspended particles and (c) large scale scattering due to refractive index variations. In this paper, only pure seawater scattering and particle scattering with coefficients $b_p(\lambda)$, and b_{sw} (λ) respectively are studied. Sothe total scattering coefficient $b(\lambda) = b_p(\lambda) + b_{sw}(\lambda)$

To study the effects of multiple scattering, the scattering phase function (SPF) $\beta(\theta, \lambda)$ is used to describe the energy distribution at various scattering angle θ and scattered light with the equation shown below

$$2\pi \oint_0^{\pi} \beta(\theta, \lambda) \sin\theta d\theta = 1 \qquad (1)$$

Since focus is on the propagation of green/blue region of visible light, we can simply omit the parameter λ.

The SPF of small scale scattering is similar to Rayleigh scattering as

$$\beta_{sw}(\theta) = (1 + 0.835 \cos^2\theta)\, 0.06225 \qquad (2)$$

For small forward angles seawater SPF is strongly peaked. This is measured for selected water types when the particle scattering occurred by large suspended particles are taking into consideration. Several closed-form expressions have been adopted to represent the SPF of seawater such as HG function and two terms HG (TTHG) function. The HG function is used to describe the SPF of dispersive medium as

$$\beta_{HG}(\theta) = (1 + g^2 - 2g\cos\theta)^{3/2}(1 - g2/4\pi) \qquad (3)$$

Where g is the average cosine of θ and θ is the scattered angle. However, the HG function differs from previously studied measurement of seawater SPF especially in small forward angles (<20°) and backward angles (>130°), and therefore underestimates the forward and backward scattering light. TTHG function is a modification of HG function and has slight improvement in small forward angles. However, the outputs of TTHG function are much smaller than the measurement in previous works for angles below 1° and larger than the measurement for angles above 140°. Note that the pure seawater scattering has little contribution to the SPF with details will be provided in the following discussion. Therefore, the SPF of our model deviates slightly from the linear interpolated PPF.

The total SPF $\beta(\theta)$ including the effects of particles and pure seawater is as

$$\beta(\theta) = \frac{bp}{b}\, \beta p(\theta) + \frac{bsw}{b} \beta sw(\theta) \qquad (4)$$

In this paper, focus is on the temporal pulse spread in opaque thickly environments such as coastal and harbor water. The typical value of b_{sw} is 2.33×10^{-3} m^{-1} for blue/green region of visible light spectrum which implies the particle scattering coefficient $b_p >> b_{sw}$ and little contribution to the SPF made by small scale scattering.

2. System Model

In this part, general link geometry and the system model for UWOC links are discussed. Consider a UWOC system having a precisely aligned line-of-sight (LOS) receiver and link, which is positioned on a plane orthogonal to the trajectory of the light beam. The pulse of beam emitted from the source is deteriorated temporally when it pass through the underwater channel, and then polluted by receiver noises. Here the underwater channel is considered as a homogeneous medium of ideal isotropic without any turbulence or current flow. So the underwater this optical channel can be considered as a linear time-invariant (LTI) system.

In an ideal photon counting receiver, the number of photons detected in each slot obeys the Poisson distribution. Practically the receiver noise is a combination of radiation noise, shot noise, dark current noise, and thermal noise. So the UWOC system can be modeled as

$$y(t) = n(t) + h(t) * x(t) \qquad (5)$$

Where x(t) and y(t) are the transmit and receive signals, respectively. h(t) is the impulse response of UWOC links. n(t) is the noise signal.

III. IMPULSE RESPONSE MODELING

1. Monte Carlo Simulation

In Monte Carlo method, a set of photons are emitted by the source with specific transmission angle. Each photon with the channel undergoes absorption and scattering. This can be modeled by changing the basic parameters of each and every photon such as the direction of transmission, location, weight and time of propagation. These parameters are noted when the photon reaches the receiver. The channel impulse response and channel loses can be statistically calculated by analyzing the basic parameter changes of all the received photons. The basic attributes of each photon include the photon position in Cartesian coordinates (x, y, z), the direction of transmission described by zenith angle θ and azimuth angle $\varphi 1$, propagation time t and weight w. For the source with narrow emission aperture, each photon is initialized at the position (0, 0, 0) with zero start time and unit weight. The emitted direction of each photon depends on both the divergence angle and angular intensity distribution of the source.

Each photon may interact with the medium when propagating s distance, which can be determined by $s = -\ln \xi s/c$ with ξs as a uniform distributed random variable in the interval of [0, 1]. After the distance between two interactions s being determined, the spatial position and propagation time can be updated accordingly. The photon weight can be updated by

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$$W^{i+1} = \left(1 - \frac{a}{c}\right) W^{i} \qquad (6)$$

Where W^i is the photon weight after the i^{th} interaction with medium. The scattering may also change the direction of photon path (trajectory) which changes with the scattering zenith angle θ_s as

$$\xi\theta = 2\pi \int^{\theta s} \beta(\theta) \sin\theta d\theta \qquad (7)$$

Where ξ_θ is an uniform distributed random between 0 and 1 with $\beta(\theta)$ as the SPF. θ_s can be obtained by solving (8) numerically.
Then the scattering azimuth angle φ_s can be computed by

$$\varphi_s = 2\pi\xi_\varphi \qquad (8)$$

Where ξ_φ is a uniformly distributed random variable
The value of photon weight threshold is set as $10^{-6.}$ The tracking of each photon should be stopped either the photon reaches the receiver plane or its weight is lower than certain threshold. To prepare a histogram of received photon intensity versus propagation time for unit transmit intensity repeat all the above steps for all the photons and record all the basic parameter changes. Histogram can be prepared by adding the weight of photons having the same propagation time. Channel impulse response can be calculated by normalizing it by the total transmit weight. By this reason, the time resolution corresponds to the temporal bin size of this histogram and is set to $t_d = 10^{-10}$ s.

2. Double Gamma Functions Model

In this part, closed-form expression of the impulse response for UWOC links is described. For small values of the attenuation length (also known as optical thickness) τ defined as $\tau = cL$ with c as the extinction coefficient and L as the physical link range, the non-scattering light dominates at the receiver side where the path loss versus τ follows the Beer's law.

As τ increases, the transition between these two regions occurs, after which the multiple scattering light dominates and the path loss deviates from Beer's law also implies negligible temporal dispersion of UWOC links in the non-scattering light dominating region, which is verified by simulating the impulse response in clean water, and increasing temporal dispersion in the multiple scattering light dominating region as τ increases. The closed-form expression of the double Gamma functions is

Coefficient	Value
Quantum efficiency η	0.8
Wavelength of the source λ	532 nm
Electronic bandwidth B	20 GHz
Dark current I_{dc}	1.226 nA
Noise figure F	4
Equivalent temperature T_e	290 K
Load resistance R_L	100 Ω

TABLE I
COEFFICIENTS FOR OUR SYSTEM

$$h(t) = C1\Delta te^{-C2\Delta t} + C3\Delta te^{-C4\Delta t}, \ (t \geq t0) \qquad (9)$$

whereC1, C2, C3and C4are the four parameters to be solved and $\Delta t = t - t0$ where t is the time scale and $t0 = L/v$ is the propagation time which is the ratio of link range L over light speed v in water. Then the least C value can be determined from the Monte Carlo simulation and double gamma function with the help of Harmony Search Algorithm.

IV. HARMONY SEARCH ALGORITHM

In the basic Harmony search algorithm, each solution is called a "harmony". It is represented by an n -dimension real vector. An initial population of harmony vectors are randomly generated and stored within a Harmony Memory (HM). By using a memory consideration a new candidate harmony is generated from the elements in the HM operation either by an itch adjustment operation or random re-initialization.

Finally, the HM is updated by comparing the new candidate harmony and the worst harmony vector in the HM. The worst harmony vector will be replaced with the new candidate vector if it is better than the worst harmony vector. The above process is repeated until a certain termination criterion is met. The Harmony Search algorithm has three fundamental phases: HM initialization, improvisation of New Harmony vectors and updating of the HM. The following discussion addresses details about each stage.

Step 1: Initializing the problem and algorithm parameters

In general, the global optimization problem can be summarized as follows: min $f(x)$: $x(j) \in [l(j), u(j)]$, j=1,2,…..n. Where f(x) is the objective function, x = (x(1), x(2),...,x(n)) is the set of design variables, n is the number of design variables, and l(j) and u(j) are the lower and upper bounds for the design variable x(j) ,respectively. The parameters for HS are the harmony memory size, i.e., the number of solution vectors lying on the harmony memory (HM), the harmony-memory consideration rate (HMCR), the pitch adjusting rate (PA R), the distance bandwidth (BW) and the number of improvisations (NI) which represents the total number of iterations. It is obvious that the performance of HS is strongly influenced by parameter values which determine its behavior.

Step 2: Harmony memory initialization

In this stage, initial vector components at HM, i.e., HMS vectors are configured. Let $x_i=\{x_i(1), x_i(2),...,x_i(n)\}$ represent the i^{th} randomly-generated harmony vector: $xi(j) = l(j) + (u(j) - l(j)) \cdot rand(0, 1)$ for j = 1 , 2 ,...,n and i = 1 , 2 ,...,HMS, where rand(0 , 1) is a uniform random number between 0 and 1. Then, the HM matrix is filled with the HMS harmony vectors as follows:

$$\text{HM} = \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \vdots \\ \mathbf{x}_{HMS} \end{bmatrix}$$

Step 3: Improvisation of New Harmony vectors

In this phase, by the following three operators: memory consideration, random re-initialization and pitch adjustment a New Harmony vector x_{new} is formed. Generating a new harmony is known as 'improvisation'. In the memory consideration step, the value of the first decision variable $x_{new}(1)$ for the new vector is chosen randomly from any of the values already existing in the current HM i.e., from the set $\{x_1(1), x_2(1), \ldots, x_{HMS}(1)\}$. For this operation, a uniform random number r_1 is generated within the range [0 , 1] .If r_1 is less than HMCR , the decision variable $x_{new}(1)$ is generated through memory considerations; other-wise, $x_{new}(1)$ is obtained from a random re-initialization between the search bounds $[l(1), u(1)]$. Values of the other decision variables $x_{new}(2), x_{new}(3), \ldots, x_{new}(n)$ are also chosen accordingly. Therefore, both operations, memory consideration and random re-initialization, can be modeled as follows:

$$x_{new}(j) = \begin{cases} x_i(j) \in \{x_1(j), x_2(j) \ldots\ldots x_{HMS}(j)\} \text{with probability HMCR} \\ l(j) + (u(j) - l(j)).\text{rand}(0,1) \text{ with probability } 1 - \text{HMCR} \end{cases}$$

Every component obtained by memory consideration is further examined to determine whether it should be pitch-adjusted. For this operation, the Pitch-Adjusting Rate (PAR) is defined as to assign the frequency of the adjustment and the Bandwidth factor (BW) to control the local search around the selected elements of the HM. The pitch adjusting is calculation as follows:

$$x_{new}(j) = \begin{cases} x_{new}(j) \pm \text{rand}(0,1).BW \text{with probability } PAR \\ x_{new}(j) \text{ with probability} (1 - \text{PAR}) \end{cases}$$

Pitch adjusting is responsible for generating new potential harmonies by slightly modifying original variable positions. Such operations can be considered similar to the mutation process in evolutionary algorithms. Therefore, the decision variable is either perturbed by a random number between 0 and BW or left unaltered. In order to protect the pitch adjusting operation, it is important to assure that points lying outside the feasible range [l,u] must be reassigned i.e., truncated to the maximum or minimum value of the interval.

Step 4: Updating the harmony memory

After a New Harmony vector x_{new} is generated, the harmony memory is updated by the survival of the fit competition between x_{new} and the worst harmony vector x_w in the HM. Therefore x_{new} will replace x_w and become a new member of the HM in case the fitness value of x_{new} is better than the fitness value of x_{new}.

Step 5: Termination criterion

Repeat steps 2 and 3 until the termination criterion is satisfied.

V. PERFORMANCE EVALUATION

The performance analysis of UWOC systems is directly based on the model of the impulse response developed in the previous section. The ISI effect as well as BER performance is evaluated, and then calculate the channel bandwidth for coastal and harbor water. . The parameters for system configuration are listed in Table I.

BER Performance & Channel Bandwidth

UWOC system operating in turbid water environment in the presence of ISI is considered.. The transmitter intends to transmit data using OOK scheme, i.e., representing the low bits and high bits by empty and pulse slots respectively. The ISI introduced by the temporal spread of beam pulse degrades the system performance and can be analyzed equivalently at baseband regardless of the presence of ISI .The detection process can be modeled by integrating the received signal over the slot duration and adding the noise. Then the output sequence of the detection process is sent through the ZF equalizer where its tap weights depend on the channel impulse response. The channel bandwidth for coastal and harbor can be directly calculated based on the double Gamma functions model of channel impulse response.

VI. CONCLUSION

In this paper, the temporal dispersion of UWOC links due to the multiple scattering effects in coastal environments is presented. A closed-form expression of Monte Carlo simulations using actual SPF for various link ranges and double Gamma functions are presented for various link ranges in coastal sea water conditions. Harmony search Algorithm is proposed to model the channel impulse response and quantify the channel time dispersion under different conditions of water type, link distance, and the transmitter/receiver parameters. The results show that the link bandwidth decreases for higher attenuation lengths where light suffers more temporal spreading, and the ISI reduce the BER performance for high bit rates system without equalization. ZF equalizer designed based on the double Gamma functions model has been adopted in high speed UWOC systems and validated to improve the BER performance of system.

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