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Signal-to-noise ratio reduction due to oceanic turbulence in oceanic wireless optical communication links

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ABSTRACT

The effect of oceanic turbulence on the signal-to-noise ratio (*SNR*) at the receiver of an oceanic wireless optical communication (OWOC) link is studied. To quantify such effect, the metric employed is the reduction in the *SNR* when oceanic turbulence is present. *SNR* reduction due to oceanic turbulence is formulated by subtracting the 10 log (*SNR*) evaluated at the receiver in the presence of turbulence from the 10 log (*SNR*) evaluated at the receiver in the absence of turbulence. Classical *SNR* formula which is function of the received optical power, noise and optical detector parameters is utilized. As the average received power, our earlier result that uses a Gaussian optical source field and a finite Gaussian receiver aperture in atmospheric turbulence is adapted for oceanic turbulence and such found average received power is inserted in the *SNR* expression. OWOC links that use collimated Gaussian optical sources at the transmitter and PIN photodiode, avalanche photodiode (APD) at the receiver, are analyzed. Results that present the variations of the *SNR* reduction due to oceanic turbulence against the changes in the source, oceanic turbulence and the optical receiver parameters are reported.

1. Introduction

OWOC links are becoming very popular because of their capability to handle very high data bit rates in oceanic medium. For this reason, in the last several years, researchers are paying more attention to analyze and understand the various aspects of performance of OWOC links. Within this scope, underwater optical wireless communication systems are analyzed in a general coverage [1–4]. Performances of underwater optical wireless communication links in various configurations such as the ones employing multi-pulse pulse-position modulation receivers and spatial diversity [5], MIMO [6], multi-hop [7], operations in oceanic turbulence of systems with M-ary OAMSK modulation [8] and laser beam propagation [9] are investigated. Another measure of performance in OWOC links is the bit-error-rate (BER) which is reported under oceanic turbulence for the focused Gaussian beams [10], phase-locked partially coherent flat-topped array laser beam [11], asymmetrical optical beams [12], multimode beams [13] and Gaussian beam experiencing aperture averaging [14]. Also, the wave structure functions [15,16] and the scintillation indices [17–19] that form the basis for the BER investigations are studied in oceanic turbulence.

Other aspects of OWOC links are scrutinized for the outage analysis of relay-assisted systems [20], SIMO detection schemes [21] and channel characterization [22,23]. Works related to the spectral changes in stochastic light beams [24], intensity and coherence properties of light [25], coma aberration on aperture averaged scintillations [26] in turbulent ocean exist in literature.

SNR is one of the most important performance criteria in the design of an OWOC. In general, *SNR* is expressed in the absence of turbulence [27]. When there is turbulence, the received power occurring in the *SNR* is obtained with the inclusion of the random field due to turbulence. In our earlier works, the received power expression is obtained by the extended Huygens–Fresnel method for turbulent atmosphere [28] where the same formulation with the oceanic turbulence power spectrum is used in this paper. When OWOC links operate in turbulent ocean, it is crucial to have a sound understanding on how the presence of oceanic turbulence will degrade the *SNR* in the OWOC links.

In this paper, we have elaborated the variants in the *SNR* of an OWOC link by including in the *SNR* expression, the average received power originating from oceanic turbulence. As the result, we have explicitly investigated in detail, the effects of oceanic turbulence on the received *SNR* when a collimated Gaussian beam laser source and a finite sized aperture receiver having a PIN photodiode or avalanche photodiode (APD) detector are used in the OWOC link. To our knowledge, *SNR* reduction due to oceanic turbulence is not reported in the literature. The existing studies [5–14] mainly cover the BER analysis in the presence of oceanic turbulence but *SNR* reduction analysis presented in the current paper reflects a different aspect of system performance. Our results will be helpful to OWOC system designers in improving the

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performance of the wireless optical communication links operating in oceanic turbulence.

2. Formulation

In a wireless optical communication link, *SNR* at the receiver in the absence of turbulence, which we define by the subscript *vacuum* denoting *SNR* in vacuum, is given by [27]

$$(SNR)_{vacuum} = \frac{\left(MR_0P_R\right)^2}{2qB\left(R_0P_R + R_0P_B + I_{db}\right)M^2F_n + 4K_BTB/R_L} \tag{1}$$

where M is the avalanche multiplication factor of APD which reduces to unity for the PIN photodiode, R_0 is the detector responsivity in A/watt, P_R is the received optical power in watts, $q = 1.60217662 \times 10^{-19}$ is the electronic charge in Coulomb or Amp.sec, B is the receiver bandwidth in Hz, P_B is the background noise power in watts which is taken in our evaluations to be P_R/BNF, *BNF* being the background noise factor, I_{db} in Amp is the bulk dark current when APD is used and is the dark current when PIN photodiode is used, F_n is the excess noise factor arising due to random nature of multiplication factor for the APD detector which is equal to unity for PIN photodiode, $K_B = 1.3807 \times 10^{-23}$ is the Boltzmann's constant in Joules per degree Kelvin [J/(°K)], T is the absolute temperature in degree Kelvin (°K) and R_L is the equivalent load resistance in Ω. The surface dark current of APD is usually quite small, thus in Eq. (1), it is not included.

Considering oceanic turbulence, we replace the received optical power P_R by the average received optical power $\langle P_R\rangle$ obtained when a collimated Gaussian optical beam propagates in the turbulent ocean, so we find the *SNR* at the receiver of an OWOC link operating in the presence of oceanic turbulence as

$$(SNR)_{turb} = \frac{\left(MR_0\langle P_R\rangle\right)^2}{2qB\left(R_0\langle P_R\rangle + R_0P_B + I_{db}\right)M^2F_n + 4K_BTB/R_L}. \tag{2}$$

In our earlier work [28], the average received optical power in the presence of atmospheric turbulence is found by using a finite receiver of aperture size R weighted by the Gaussian function. In the current paper, we have derived the formulation of the average optical power in the presence of oceanic turbulence as received by a finite size receiver aperture. In this derivation, similar steps of the formulation in [28] which is valid for atmospheric turbulence are employed. Our derivation involve the power spectrum for homogeneous and isotropic oceanic turbulence which is given under equal eddy thermal diffusivity and the diffusion of salt by [29]

$$\begin{aligned}\Phi_n(\kappa) = {}& 0.388 \times 10^{-8}\varepsilon^{-1/3}\kappa^{-11/3}\left[1 + 2.35(\kappa\eta)^{2/3}\right] \\ & \times \frac{X_T}{w^2}\left(w^2e^{-A_{TT}\delta} + e^{-A_{SS}\delta} - 2we^{-A_{TS}\delta}\right),\end{aligned} \tag{3}$$

where κ is the spatial frequency, $\delta = 8.284(\kappa\eta)^{4/3} + 12.978(\kappa\eta)^2$ $A_{TT}(\kappa) = 1.863\times10^{-2}$, $A_{SS}(\kappa) = 1.9\times10^{-4}$, $A_{TS}(\kappa) = 9.41\times10^{-3}$, w is a unitless parameter giving the ratio of temperature to salinity contributions to the refractive index spectrum which ranges from −5 to 0, the end values reflecting the temperature dominating and salinity-induced oceanic turbulence, respectively, X_T denotes the rate of dissipation of mean-squared temperature, ε is the rate of dissipation of kinetic energy per unit mass of fluid, η is the Kolmogorov microscale, known also as the inner scale.

Thus, utilizing the result in [28] and the power spectrum of oceanic turbulence in Eq. (3), the average received optical power in oceanic turbulence is found for a coherent collimated Gaussian optical beam wave source as

$$\langle P_R\rangle = N/D_t, \tag{4}$$

where $\langle\cdot\rangle$ denotes the ensemble average over the oceanic turbulence statistics,

$$N = 0.25\pi\left(A_sk\alpha_s/L\right)^2, \tag{5}$$

A_s and α_s are the amplitude in V/m and the size in meters of the collimated Gaussian source field, respectively, $k = 2\pi/\lambda$, λ is the wavelength, L is the link length,

$$\begin{aligned}D_t = {}& \left(0.25\alpha_s^{-2} + \rho_0^{-2} + 0.25\alpha_s^2k^2/L^2\right) \\ & \times\left[R^{-2} + \left(k^2\alpha_s^2/L^2\right)\left(1 + 4\alpha_s^2\rho_0^{-2} + \alpha_s^4k^2/L^2\right)^{-1}\right],\end{aligned} \tag{6}$$

R is the receiver aperture size and ρ_0 is the spatial coherence length of a spherical wave propagating in the oceanic turbulent medium which is found from the integral [30]

$$\rho_0 = \left[\frac{\pi^2}{3}k^2L\int_0^\infty \kappa^3\Phi_n(\kappa)\,d\kappa\right] \tag{7}$$

as [30]

$$\rho_0 = \left[3.603 \times 10^{-7}k^2L(\varepsilon\eta)^{-1/3}\frac{X_T}{2\omega^2}\left(0.483\omega^2 - 0.835\omega + 3.38\right)\right]^{-0.5}. \tag{8}$$

We note that the average power reported in Eq. (4), together with Eqs. (5), (6) and (8) is an application of our earlier result [28] on the average power received by a finite receiver aperture in atmospheric turbulence, to the average power received by a finite receiver aperture in oceanic turbulence. In the absence of oceanic turbulence, the received optical power P_R in Eq. (1) is found by taking $\rho_0 = \infty$, which makes

$$P_R = N/D_v \tag{9}$$

where

$$D_v = \left(0.25\alpha_s^{-2} + 0.25\alpha_s^2k^2/L^2\right)\left[R^{-2} + \left(k^2\alpha_s^2/L^2\right)\left(1 + \alpha_s^4k^2/L^2\right)^{-1}\right]. \tag{10}$$

As the measure of *SNR* reduction due to oceanic turbulence in OWOC links, the following definition is made:

$$SNR \text{ reduction} = 10\log(SNR)_{vacuum} - 10\log(SNR)_{\text{turb}}. \tag{11}$$

Unit of the *SNR* reduction in Eq. (11) is dB which is evaluated and plotted in Section 3 for various source, oceanic turbulence and receiver parameters.

3. Results

In Figs. 1–6, the variations of the *SNR* reduction due to oceanic turbulence in OWOC links as provided in Eq. (11) are plotted against the variations of the oceanic turbulence parameters for different avalanche multiplication factors, receiver aperture sizes and link lengths. It is seen from Fig. 1 that as the ratio of temperature to salinity contributions to the refractive index spectrum, w increases, i.e., as the oceanic turbulence goes from temperature dominated structure to salinity induced structure, *SNR* reduction increases for both receiver aperture sizes, no matter whether the detection is done by an APD ($M = 80$, $F_n = 5$) or by a PIN ($M = 1$, $F_n = 1$) photodiode. This is physically reasonable because increase in *SNR* reduction means that oceanic turbulence effects are heavier on the degradation of *SNR* which is the case when the ratio of temperature to salinity contributions to the refractive index spectrum becomes more salinity dominated, i.e., when the oceanic turbulence becomes stronger. Another interesting observation from Fig. 1 is that at the fixed ratio of temperature to salinity contributions to the refractive index spectrum, being valid for both APD or PIN photodiode, larger receiver aperture size, which reduces the oceanic turbulence effect due to aperture averaging effect, makes the *SNR* reduction smaller. Again, examining Fig. 1 at the fixed ratio of temperature to salinity contributions to the refractive index spectrum, being valid for both receiver aperture sizes, use of APD is advantageous since it yields smaller reduction in *SNR* due to oceanic turbulence.

Fig. 2 shows that increase in the ratio of temperature to salinity contributions to the refractive index spectrum, w, causes the *SNR* reduction to increase for both link lengths, L, no matter whether an APD ($M = 80$, $F_n = 5$) or a PIN ($M = 1$, $F_n = 1$) photodiode is used in the detection.