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Amplify-And-Forward Based Cascaded RF-UWOC System

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Abstract- ***A cascaded radio frequency-underwater wireless optical communication (RF-UWOC) system using an amplify-and-forward relay is considered. UWOC supports high speed communication for underwater surveillance, monitoring of climate change, and different deep-sea mining activities making it a s suitable substitute to underwater acoustic communication. The proposed fixed-gain AF based cascaded radio-optical system can connect underwater with land. The system comprises of Nakagami-m faded radio link and mixture Exponential-Generalized Gamma (EGG) faded UWOC link. Salinity, air bubbles, and thermal fluctuations in water causes underwater optical turbulence (UOT). Optical signals are modulated by subcarrier intensity modulation technique at the relay and heterodyne or direct detection is performed at destination. For this proposed communication system, outage and error analyses are carried out. It is observed that the performance of the considered system deteriorates more because of the underwater optical turbulence (UOT) due to thermal fluctuations and air bubbles as compared to UOT introduced by salinity.***

Index Terms- ***Amplify-and-forward, bit error-rate, outage probability, radio frequency, and underwater wireless optical communication.***

I. INTRODUCTION

Communication inside water can be performed wirelessly using either acoustic signals or optical signals. Underwater optical communication (UWOC) has various advantages such as fast speed, energy efficiency, secure, cheap, and low attenuation. This technology can be used for climate change monitoring, deap-sea explorations, underwater-surveillance, underwater data collection, and disaster management [1]–[3]. Salinity, air bubbles, and thermal fluctuations cause underwater optical turbulence (UOT) which reduces the optical intensity [4], [5]. Apart from UOT, photon absorption and light scattering also affect the performance of such systems and reduces the coverage area for communication.

Previous works in UWOC, characterized UOT by Lognormal distribution as done in free space optical communication (FSO) for characterizing weak irradiance [6]. In [7], UWOC system considering spatial diversity and optical pre-amplification was studied also assuming Lognormal distributed UOT. UWOC systems using multi-pulse position modulation scheme and spatial diversity was studied in [8], where the system performance was limited due to the impact of Lognormal-irradiance, receiver noise, and inter symbol interference was evaluated. Multiple-input-multiple-output (MIMO) based UWOC systems employing on-off keying (OOK) modulation scheme and considering Lognormal distributed scintillations was studied in [9]. Impact of light scattering, Lognormal-UOT, and photon absorption was studied on BER of multi-hop UWOC systems in [10]. However, through various experiment its was observed that the profile refractive index profile variations for FSO communication differs from refractive index fluctuation profile inside water. In [11], mixture Exponential-Generalized Gamma (EGG) faded UOT was used, which modeled the impact of salinity, air bubbles, and thermal fluctuations. Considering this UWOC channel model, error analysis of a decode-and-forward (DF) based cascaded RF-UWOC system was performed in [12].

Performance analysis of a fixed-gain amplify-and-forward (AF) based cascaded RF-UWOC system is performed in this paper, Nakagami-*m* distributed radio link and EGG distributed optical link. Such system has applications whenever communication has to be established between core network on land with underwater. Subcarrier intensity modulation (SIM) technique is implemented to modulate the underwater optical signal, which is performed at relay and for detection at destination any of direct detection or heterodyne detection technique can be used [13]. This manuscript contributes by providing outage analysis and error analysis of different modulation techniques for the proposed system using the derived statistical properties of instantaneous SNR,i.e., PDF (probability density function) and CDF (cumulative distribution function). In the given analysis, the unified impact of air bubble concentration, thermal fluctuations, saltiness inside water and radio fading on the cascaded RF-UWOC system is considered.

II. SYSTEM AND CHANNEL MODEL

Consider a dual-hop mixed RF/UWOC system, where the terrestrial source (S) communicates with the underwater destination (D), using an AF relay (R) mounted on the ship as shown in Fig 1. In this system, S-R RF link is characterized by Nakagami-*m* distributed fading and R-D UWOC link is modelled by EGG distributed turbulence. SIM technique is used to modulate optical signals, therefore giving us flexibility to use any of the RF modulation techniques. The signal received by the ship (R) from the base station (S) can be expressed as

$$y_1 = h_1 x + e_1, \qquad (1)$$

where h_1 describes S-R channel gain of the S-R_1 link assumed to be Nakagami-assumed to be Nakagami-m distributed, e_1

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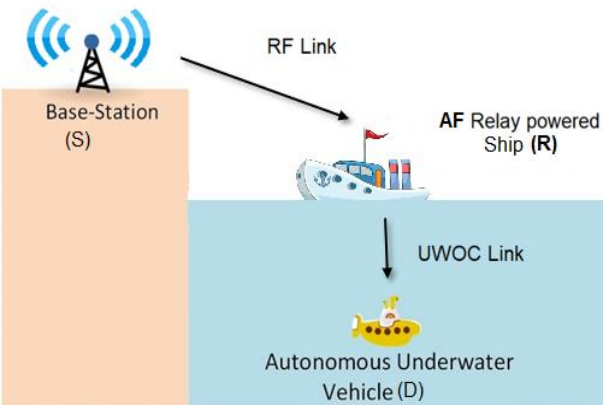

Fig. 1. Cascaded RF-UWOC system model using AF relay

represents normal noise (AWGN) $N(0,\sigma_1^2)$, and x is the signal transmitted by S. Instantaneous SNR (signal-to-noise ratio) of the radio link is given by, $\gamma_1 = |h_1|^2\bar{\gamma}_1$, where $\bar{\gamma}_1$ represents S-R link's average SNR. As the radio link undergoes Nakagami-m distribution, through random variable transformation, γ_1 can be shown to undergo Gamma distribution having PDF [14]

$$f_{\gamma_1}(\gamma) = \frac{m^m \gamma^{m-1}}{\Gamma(m)\bar{\gamma}_1} exp\left(-\frac{m\gamma}{\bar{\gamma}_1}\right), \quad (2)$$

where m shows the extent of Nakagami fading in the soure to
relay link. From the PDF of γ_1, CDF is given by

$$F(\gamma) = \frac{1}{\Gamma(m)}\gamma\left(m, \frac{m\gamma}{\bar{\gamma}_1}\right), \quad (3)$$

where, Γ(.) stands for Gamma function and γ (s, x) stands for lower incomplete Gamma function. As the relaying protocol is amplify-and-forward, the radio signal received from S is first amplified by an amplification factor, taken as Ω. By using SIM technique, the amplified RF signal is then transformed to optical signal, which is then sent to the destination. The optical signal is then converted into corresponding electrical signal at the receiver using photodetector using any of the detection techniques. This electrical signal can be written as

$$\begin{aligned} y_2 &= \Omega I_2 \eta_2 (h_1 x + e_1) + e_2, \\ &= \Omega I_2 \eta_2 h_1 x + \Omega I_2 \eta_2 e_1 + e_2 \end{aligned} \quad , \quad (4)$$

where, η_2 is the opto-electric conversion coefficient, I_2, is the irradiance or UOT of the underwater optical link, and e_2 is the normal distributed noise, $N(0,\sigma_2^2)$. One of the most important factor characterizing UWOC link is its instantaneous SNR given by, $\gamma_2 = (I_2\eta_2)^p/\sigma_2^2$, where p is equal to 1 for heterodyne detection technique and p is equal to 2 for direct detection technique. The average SNR of the UWOC link, i.e., the SNR of the optical signal received at the photodetector at D, $\bar{\gamma}_2$, is related to electrical SNR μ_p, as $\bar{\gamma}_2 = \frac{\mu_p E[I^p]}{E[I]^p}$ [12].

According to the recent experimental studies, underwater turbulence affecting the optical signal is best characterized by the EGG distribution. The combined expression of PDF of UOT for both types of detection can be expressed as [11]

$$f_{\gamma_2}(\gamma) = \frac{\varphi}{p\gamma} G_{0,1}^{1,0}\left(\frac{1}{\lambda}\left(\frac{\gamma_2}{\mu_p}\right)^{\frac{1}{p}}\middle|\begin{matrix}-\\1\end{matrix}\right) + \frac{\theta(1-\varphi)}{p\gamma\Gamma(\alpha)} G_{0,1}^{1,0}\left(\frac{1}{\beta^\theta}\left(\frac{\gamma_2}{\mu_p}\right)^{\frac{\theta}{p}}\middle|\begin{matrix}-\\\alpha\end{matrix}\right), \quad (5)$$

where, φ stands for weight of mixture in EGG distribution. It is values vary from 0 to 1. Other parameters are λ, which is the variation parameter for Exponential distribution and α, β, θ are the variation parameters for Generalised Gamma distribution. The CDF of γ_2 is obtained as

$$F_{\gamma_2}(\gamma) = \varphi G_{1,2}^{1,1}\left(\frac{1}{\lambda}\left(\frac{\gamma_2}{\mu_p}\right)^{\frac{1}{p}}\middle|\begin{matrix}1\\1,0\end{matrix}\right) + \frac{(1-\varphi)}{\Gamma(\alpha)} G_{1,2}^{1,1}\left(\frac{1}{\beta^\theta}\left(\frac{\gamma_2}{\mu_p}\right)^{\frac{\theta}{p}}\middle|\begin{matrix}1\\\alpha,0\end{matrix}\right). \quad (6)$$

III. STATISTICAL PROPERTIES OF INSTANTANEOUS SNR OF THE PROPOSED SYSTEM

A. DEFINITION

From the expressions in (4) and instantaneous SNRs of the terrestrial and underwater links, the SNR of considered system, γ_z is given by

$$\gamma_z = \frac{\gamma_1\gamma_2}{\gamma_1 + G} \quad (7)$$

B. Cl

For the proposed system, CDF of the system SNR, can be written as

$$\begin{aligned} F_{\gamma_z}(\gamma) &= Pr\left[\frac{\gamma_1\gamma_2}{\gamma_1+G} \le \gamma\right], \\ &= \int_0^\infty Pr\left[\frac{\gamma_1\gamma_2}{\gamma_1+G} \le \gamma | \gamma_2\right] f_{\gamma_2}(\gamma_2) d\gamma_2 \\ &= \int_0^\infty Pr\left[\gamma_1 \le \frac{\gamma(\gamma_1+G)}{\gamma_2} | \gamma_2\right] f_{\gamma_2}(\gamma_2) d\gamma_2 \end{aligned} \quad (8)$$

Using (3) and (5) in (8), we obtain

$$F_{\gamma_z}(\gamma) = I_1 + I_2 \quad (9)$$

where,

$$I_1 = \frac{\varphi}{p\Gamma(m)} \int_0^\infty \gamma_2^{-1} \gamma\left(m, \frac{m\gamma(\gamma_2+G)}{\bar{\gamma}_1\gamma_2}\right) G_{0,1}^{1,0}\left(\frac{1}{\lambda}\left(\frac{\gamma_2}{\mu_p}\right)^{\frac{1}{p}}\middle|\begin{matrix}-\\1\end{matrix}\right), \quad (10)$$

$$I_2 = K_1 \int_0^\infty \gamma_2^{-1} \gamma\left(m, \frac{m\gamma(\gamma_2+G)}{\bar{\gamma}_1\gamma_2}\right) G_{0,1}^{1,0}\left(\frac{1}{\beta^\theta}\left(\frac{\gamma_2}{\mu_p}\right)^{\frac{\theta}{p}}\middle|\begin{matrix}-\\\alpha\end{matrix}\right), \quad (11)$$

and $K_1 = \frac{\theta(1-\varphi)}{p\Gamma(\alpha)\Gamma(m)}$.

Lower incomplete Gamma function can be expressed in series as

$$\gamma(s,z) = \Gamma(s)\left(1 - \exp(-z)\sum_{i=0}^{m-1}\frac{z^i}{k!}\right)$$

(12)

Using (12) and [15, Eq. (8.4.3.2)], in (10), I1 is given by

$$I_1 = 1 - \sum_{k=0}^{m-1}\sum_{l=0}^{k}\frac{\varphi m^k \gamma^k G^{k-l}}{p\bar{\gamma}_1^k}\binom{k}{l} exp\left(-\frac{m\gamma}{\bar{\gamma}_1}\right) \times \int_0^\infty \gamma_2^{l+k-1}\, G_{1,0}^{0,1}\left(\frac{\bar{\gamma}_1\gamma_2}{mG\gamma}\middle|\begin{matrix}1\\-\end{matrix}\right) G_{0,1}^{1,0}\left(\frac{1}{\lambda}\left(\frac{\gamma_2}{\mu_p}\right)^{\frac{1}{rp}}\middle|\begin{matrix}-\\1\end{matrix}\right) d\gamma_2.$$

(13)

Now using [16, Eq. (21)] in (13), I_1 is given by

$$I_1 = 1 - \sum_{k=0}^{m-1}\sum_{l=0}^{k} A_1\gamma^l\, exp\left(-\frac{m\gamma}{\bar{\gamma}_1}\right) G_{0,p+1}^{p+1,0}\left(W_1\gamma\middle|\begin{matrix}-\\\xi\end{matrix}\right),$$

(14)

Where $A_1 = \frac{\varphi m^l p^l}{(2\pi)^{\frac{p-1}{2}}\bar{\gamma}_1^l}\binom{k}{l}$, $W_1 = \frac{mG}{\lambda^p p^p \mu_p \bar{\gamma}_1}$, and $\xi = \Delta(p,1), k-l$.

Now for solving I_2, using (12) and [15, Eq. (8.4.3.2)] in (11), we have

$$I_2 = 1 - \sum_{k=0}^{m-1}\sum_{l=0}^{k}\frac{(1-\varphi)\theta m^k \gamma^k G^{k-l}}{p\Gamma(\alpha)\bar{\gamma}_1^k}\binom{k}{l} exp\left(-\frac{m\gamma}{\bar{\gamma}_1}\right) \times \int_0^\infty \gamma_2^{l+k-1}\, G_{1,0}^{0,1}\left(\frac{\bar{\gamma}_1\gamma_2}{mG\gamma}\middle|\begin{matrix}1\\-\end{matrix}\right) G_{0,1}^{1,0}\left(\frac{1}{\beta^\theta}\left(\frac{\gamma_2}{\mu_p}\right)^{\frac{\theta}{p}}\middle|\begin{matrix}-\\\alpha\end{matrix}\right) d\gamma_2.$$

(15)

Now using [16, Eq. (21)] in (15), I_2 is given by

$$I_2 = 1 - \sum_{k=0}^{m-1}\sum_{l=0}^{k} A_2\gamma^l\, exp\left(\frac{-m\gamma}{\bar{\gamma}_1}\right) G_{0,p+\theta}^{p+\theta,0}\left(W_2\gamma^\theta\middle|\begin{matrix}-\\\delta\end{matrix}\right), \quad (16)$$

where, $A_2 = \frac{(1-\varphi)m^l p^{\frac{2\alpha-1}{2}}\theta^{\frac{2k-2l-1}{2}}}{(2\pi)^{\frac{p+\theta-2}{2}}\Gamma(\alpha)\bar{\gamma}_1^l}\binom{k}{l}$,

$W_2 = \left(\frac{1}{p}\right)^p\left(\frac{mG}{\theta\beta^p\mu_p\bar{\gamma}_1}\right)^\theta$, and $\delta = \Delta(p,\alpha), \Delta(\theta, k-l)$.

Therefore, by substituting (14) and (16) in (9), the CDF of the instantaneous SNR of the proposed system can be expressed as

$$F_{\gamma_z}(\gamma) = 2 - \sum_{k=0}^{m-1}\sum_{l=0}^{k}\gamma^l\, exp\left(\frac{-m\gamma}{\bar{\gamma}_1}\right)\left[A_1 G_{0,p+1}^{p+1,0}\left(W_1\gamma\middle|\begin{matrix}-\\\xi\end{matrix}\right) - A_2\, G_{0,p+\theta}^{p+\theta,0}\left(W_2\gamma^\theta\middle|\begin{matrix}-\\\delta\end{matrix}\right)\right] \quad (17)$$

C. PDF

Using (17) w.r.t. γ and [15, Eq. (8.2.30)], the PDF of the end-to-end SNR is given by

TABLE I
BER PARAMETERS FOR VARIOUS MODULATION TECHNIQUES [25]

Modulation Techniques	u	v
Coherent Binary Frequency Shift Keying (CBFSK)	0.5	0.5
Coherent Binary Phase Shift Keying (CBPSK)	0.5	1
Non-Coherent Binary Frequency Shift Keying (NBFSK)	1	0.5
Differential Binary Phase Shift Keying (DBPSK)	1	1

$$f_z(\gamma) = \sum_{k=0}^{m-1}\sum_{l=0}^{k}\frac{m\gamma^l}{\bar{\gamma}_1} exp\left(\frac{-m\gamma}{\bar{\gamma}_1}\right)\left[A_1 G_{0,p+1}^{p+1,0}\left(W_1\gamma\middle|\begin{matrix}-\\\xi\end{matrix}\right) - A_2\, G_{0,p+\theta}^{p+\theta,0}\left(W_2\gamma^\theta\middle|\begin{matrix}-\\\delta\end{matrix}\right)\right] + \sum_{k=0}^{m-1}\sum_{l=0}^{k}\gamma^{l-1} exp\left(\frac{-m\gamma}{\bar{\gamma}_1}\right) A_1 G_{0,p+2}^{p+2,0}\left(W_1\gamma\middle|\begin{matrix}-l\\1-l,\xi\end{matrix}\right) - \sum_{k=0}^{m-1}\sum_{l=0}^{k}\gamma^{l-1} exp\left(\frac{-m\gamma}{\bar{\gamma}_1}\right) \times A2G0,p+\theta+1p+\theta+1,0W2\gamma\theta-l1-l,\delta.$$

(18)

IV. PERFORMANCE ANALYSIS

This section discusses outage analysis and error analysis of binary modulation schemes for proposed AF based cascaded cooperative system.

A. Outage Probability

A communication system is said to be in outage when the SNR, γ_z, falls below a predetermined threshold value, γ_{th}. Thus, using (17), the probability of outage for the proposed cooperative system can be written as

$$P_{out}(\gamma_{th}) = 2 - \sum_{k=0}^{m-1}\sum_{l=0}^{k}\gamma_{th}^l\, exp\left(\frac{-m\gamma_{th}}{\bar{\gamma}_1}\right)\left[A_1 G_{0,p+1}^{p+1,0}\left(W_1\gamma_{th}\middle|\begin{matrix}-\\\xi\end{matrix}\right) - A_2\, G_{0,p+\theta}^{p+\theta,0}\left(W_2\gamma_{th}{}^\theta\middle|\begin{matrix}-\\\delta\end{matrix}\right)\right]. \quad (19)$$

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B. Average Bit Error Rate

The BER can be expressed using the distribution function of end-to-end SNR of the proposed system, for different binary modulation schemes, using [17, Eq. (8)] as

$$P_{eb} = A_3\int_0^\infty \gamma^{u-1}\exp(-v\gamma)\, F_{\gamma_z}(\gamma)d\gamma, \quad (20)$$

where, $A_3 = \frac{v^u}{2\Gamma(u)}$, in which 'u' and 'v' are parameters representing different binary modulation schemes in BER calculation as shown in Table I.

Substituting the CDF for the instantaneous SNR of the proposed cascaded cooperative system in (20), BER is given by

$$P_{eb} = 2A_3\int_0^\infty \gamma^{u-1}\exp(-v\gamma)d\gamma + \sum_{k=0}^{m-1}\sum_{l=0}^{k} A_1A_3\int_0^\infty \gamma^{u+l-1}\exp\left(-\left(\frac{m}{\bar{\gamma}_1}+v\right)\gamma\right)$$

$$\times G_{0,p+1}^{p+1,0}\left(W_1\gamma\middle|\bar{\xi}\right)\mathrm{d}\gamma - \sum_{k=0}^{m-1}\sum_{l=0}^{k} A_2A_3\int_0^{\infty}\gamma^{u+L-1}$$
$$\times \exp\left(-\left(\frac{m}{\bar{\gamma}_1}+v\right)\gamma\right) G_{0,p+\theta}^{p+\theta,0}\left(W_2\gamma^{\theta}\middle|\bar{\delta}\right) \qquad (20)$$

TABLE II: EGG DISTRIBUTION PARAMETERS FOR DIFFERENT UOT CONDITIONS IN UWOC SYSTEM [12]

BL	ΔT	σ_I^2	φ	λ	α	β	θ
2.4	0.05	0.15	0.21	0.33	1.43	1.18	17.20
2.4	0.20	0.22	0.17	0.12	0.16	1.52	22.88
4.7	0.05	0.20	0.35	0.35	1.04	1.58	35.94

TABLE III: EGG DISTRIBUTION PARAMETERS FOR DIFFERENT SALININTY AND AIR BUBBLES IN UWOC SYSTEM [12]

SALINITY	BL	σ_I^2	φ	λ	α	β	θ
SALTY	2.4	0.10	0.18	0.47	0.77	1.14	49.18
SALTY	4.7	0.13	0.21	0.39	0.53	1.22	35.74
FRESH	2.4	0.11	0.19	0.53	3.73	1.07	30.32
FRESH	4.7	0.12	0.21	0.46	1.25	1.15	41.33

Substituting [15, Eq. (8.4.3.1)] in (21) and then using [16, Eq.(18)] and [18, Eq.(5.6.3.1)], the BER of the proposed system can be written as

$$P_{eb} = 1 - \sum_{k=0}^{m-1}\sum_{l=0}^{k} A_1A_3\left(\frac{m}{\bar{\gamma}_1}+v\right)^{-l-u}$$
$$\times G_{1,p+1}^{p+1,1}\left(W_1\bar{\gamma}_1/(m+v\bar{\gamma}_1)\middle|\begin{matrix}1-u-l\\ \xi\end{matrix}\right)$$
$$-\sum_{k=0}^{m-1}\sum_{l=0}^{k}\frac{\theta^{u+l-\frac{1}{2}}A_2A_3}{(2\pi)^{\frac{\theta-1}{2}}}\left(\frac{m}{\bar{\gamma}_1}+v\right)^{-l-u}$$
$$\times G_{\theta,p+\theta}^{p+\theta,\theta}\left(W_2\left(\frac{\theta\bar{\gamma}_1}{(m+v\bar{\gamma}_1)}\right)^{\theta}\middle|\begin{matrix}\Delta(\theta,1-u-l)\\ \delta\end{matrix}\right). \qquad (20)$$

V. NUMERICAL RESULTS

This section discusses outage and error performance of the AF based cascaded system. Various EGG distribution parameters, characterizing different UOT scenarios, based on the values of distribution parameters, φ, λ, α, β, θ, are given in Table II and Table III. The amplification factor, Ω, is taken to be 1.2. Mathematical results are validated by matching with the Monte Carlo simulations performed in MATHEMATICA software. Equal average SNRs are assumed for both terrestrial and underwater links.

In Fig. 2, outage performance of the proposed AF based system is shown, where signals are modulated by CBFSK modulation technique, heterodyne type of detection is used at receiver, for various fading and UOT conditions. From the figure, it can be seen that the outage probability increases with the severity of the turbulence and fading conditions. It is due to the fact that higher the air bubbles concentration and/or the thermal fluctuations inside water, higher will be the value of scintillation index, which will in turn increase the impact of UOT underwater resulting in higher outage probability.

Error performance plot for the proposed cascaded system is sown in Fig. 3. CBPSK modulation scheme and direct type of detection technique are considered. Various plots are obtained for different values of salinity, various fading conditions and oceanic turbulence scenarios. From the figure, it can be seen that higher the air bubble level and/or the saltiness of water, higher is the probability of error. It can also be observed from the figure that oceanic turbulence because of higher air bubble level impacts the error performance to a much higher degree as

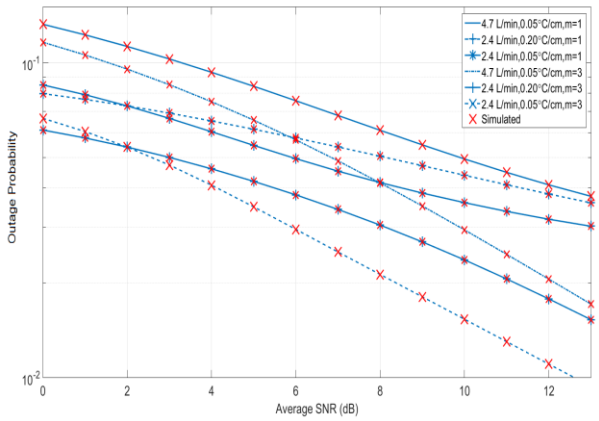

Fig. 2. Outage Probability vs SNR for the proposed AF system for different air bubbles levels, fading conditions, and underwater thermal gradient.

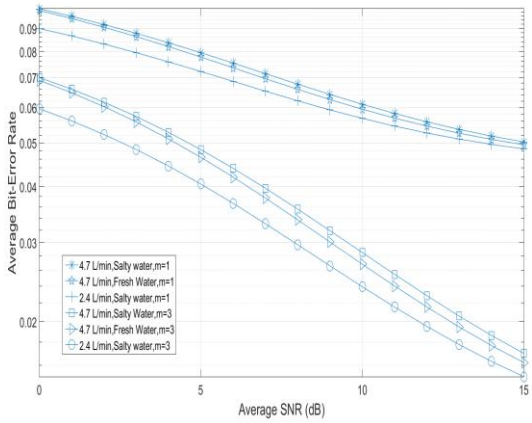

Fig. 3. Average BER of the AF based dual-hop RF/UWOC system using CBPSK and direct detection under different air bubbles concentrations in saline or fresh water source.

compared with the salinity of the water. For example, at m=3 and SNR = 9 dB, P_e rises insignificantly from 2.7×10^{-1} to 2.86×10^{-1}, when salinity of water is varied considering fresh water source and salty water source. For same conditions and for salty water scenarios, the error probability raise significantly from 2.38×10^{-1} to 2.85×10^{-1}, when the air bubbles level escalates from 2.4L/min to 4.7L/min. Also, the error performance of our system deteriorates with the increase in RF fading levels. For example, P_e increases from 2.4×10^{-1} to 5.65×10^{-1}, for salty water source with air bubbles concentration = 2.4 L/min, when m is varied from 3 to 1, thereby increasing the effect of RF fading.

VI. CONCLUSION

Novel analytical expressions have been obtained for average BER and probability of outage for the proposed fixed gain AF cascaded RF-UWOC system, using the derived mathematical expressions for statistical characteristics of its instantaneous SNR. Impact of different channel limiting factors of both terrestrial and underwater optical links (underwater optical turbulence and RF fading), has been analyzed.

It was seen that the thermal fluctuations and bubble levels resulted in higher UOT thus impacting both error performance and probability of outage of the proposed system. Their effect was to a much higher degree as compared to the degree of degradation caused by UOT resulting due to salinity of the water. Also it is seen that there is significant effect of fading on the outage and error performance of the considered system.

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