

Hybrid RF-FSO System Cascaded with UWOC Link



Sanya Anees, Smriti Rekha Baruah, Pallab Sarma

Abstract - This work presents outage analysis of a hybrid communication system, where radio frequency (RF) and free space optical (FSO) communication links transmit in parallel to the then cascaded underwater wireless optical communication (UWOC) link forming a RF/FSO-UWOC cooperative system. Optical wireless communication (OWC) is being used as a viable communication technology by researchers due to its advantages such as fast speed, cost effectiveness, and highly secure transmission. The proposed architecture connects the terrestrial and the underwater regions to form an end-to-end cooperative system. This hybrid RF/FSO back-haul link makes the system more reliable as the optical link is highly susceptible to weather conditions. The channel models considered are Nakagami-m distributed fading, Double Generalized Gamma (DGG) distributed atmospheric turbulence along with Rayleigh distributed misalignment losses and mixture of Exponential Generalized Gamma (EGG) distributed oceanic turbulence for RF, FSO, and UWOC links, respectively. Results show that outage performance is severely affected due to RF fading, DGG distributed irradiance, air bubble concentration, temperature gradient, and saltness of water source.

Index Terms-Double Generalized Gamma, Decode-and-forward, free space optical, optical wireless communication, radio-frequency, Nakagami-m distribution, underwater optical communication.

I. INTRODUCTION

Terrestrial optical wireless communication (OWC), in general called free space optical (FSO) communication has various assets over other contemporary technologies. It provides fast speed information transfer, immunity to electromagnetic interference, power efficiency, cost effectiveness, and license-free spectrum for communication [1] - [3]. But FSO link's performance gets hampered because of weather conditions, irradiance, and misalignment losses. Hybrid RF and FSO system performs simultaneous transmissions, where same information is transmitted in parallel through both the links, relay based FSO communication system or MIMO (multiple-input-multiple-output) FSO systems are possible solutions for making OWC systems reliable and better performing. The performance analysis of asymmetric cascaded RF-FSO cooperative system using amplifying-and-forwarding (AF) or decoding- and-forwarding (DF) schemes by the relay present between source and destination are studied in [6], [9], respectively.

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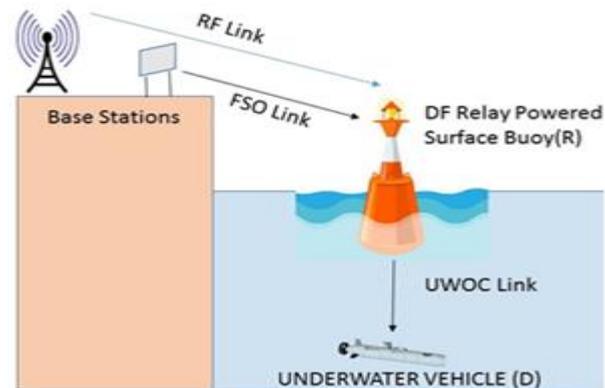


Fig.1. Hybrid RF/FSO system model cascaded with UWOC link using DF relay.

Similarly, underwater optical communication (UWOC) has been studied for deep-sea explorations for oil, monitoring of climate change, disaster management, underwater supervision, [7], [8] so as to be used an alternative to underwater acoustic communication providing high data rate and high security. Optical signals transmitted using UWOC links get degraded by scattering of light, absorption of photons, and underwater optical turbulence (UOT) [10]. In [11], bit-error-rate (BER) analysis of an UWOC link is carried out for basic on-off keying (OOK) modulation scheme and for studying the paths of photons, Monte Carlo simulation method is used. The performance for MIMO-UWOC links, where optical signals are amplified before transmission and space-time diversity used for transmission is presented in [12]. Both FSO and UWOC system can use any of the digital modulation technique using subcarrier intensity modulation (SIM). All the previously discussed UWOC systems modeled the UOT using Log-Normal distribution, as same distribution is used to characterize weak-to-moderate atmospheric scintillations in FSO systems. But [14] presents a new model using mixture of Exponential distribution and Generalized Gamma distribution (EGG) for modeling UOT. For this characterization, impact of thermal fluctuations, air bubble concentration, and saltness or brininess of the underwater are taken into consideration. Using this EGG model for the UWOC link, BER performance for cascaded RF and UWOC system are studied in [15], in which the effects of fading and UOT on system's performance is investigated. This work presents outage analysis of the DF based relayed communication system where a dual-hop RF-FSO system is cascaded with an UWOC link. Such RF/FSO-UWOC model can connect underwater transceivers with terrestrial core network as depicted in Fig.1.

The RF link works in parallel with an FSO link for hybrid system. The source-relay back-haul link consists of radio and optical atmospheric links which experience Nakagami- m distributed fading, Double Generalized Gamma (DGG) distributed scintillations, respectively, followed by relay-destination UWOC link, which is characterized using EGG distributed UOT. This analysis is done by deriving analytical expressions for outage probability of the proposed system using statistical properties of the end-to-end SNR of the proposed system. The expressions are obtained in terms of Meijer-G function, which is in-built in softwares like MATLAB and MATHEMATICA. After analytical calculations, outage analysis is performed for either direct detection or heterodyne detection schemes for atmospheric fading condition parameters, underwater optical turbulence (UOT), brininess, temperature gradient, and bubble level concentration of the water source.

II. SYSTEM MODEL

This section presents a hybrid RF/FSO system cascaded with UWOC link using a DF Relay (R) placed at surface buoy on the water surface. Hybrid RF/FSO link connects terrestrial source (S) to R located at the surface of water source. The relay decodes the received signal and then re-encodes it to transmit it to the underwater vehicle using UWOC link at destination (D). The radio link, terrestrial optical link, and underwater optical link are characterized by Nakagami- m distributed fading, DGG distributed scintillations and misalignment losses, and EGG distributed irradiance, respectively. The signals from the hybrid RF/FSO system are analyzed at R using selection combining technique (SC), where the signal having higher SNR is selected. In DF relay at the surface buoy, the obtained signal is first decoded, then re-encoded and then converted into its optical equivalent using SIM scheme. Converted optical signal at R is then transmitted to the destination using UWOC link.

RF link has SNR expressed as $\gamma_{rf} = |h_1|^2 \bar{\gamma}_{rf}$, in which $\bar{\gamma}_{rf} = E_1/\sigma^2$ denotes average SNR for the considered channel and E_1 denotes the transmit signal power. Instantaneous SNR for terrestrial optical link is expressed as $\gamma_{fso} = I_{fso}^2 \mu_{fso}$, where average optical SNR is $\bar{\gamma}_{fso} = \frac{E[I^f]}{E[I]^f} \mu_{fso}$, where 'p' denotes detection technique, which taken as 1 for heterodyne detection and 2 for direct detection. Average electrical SNR which is the average SNR of the electrical signal produced by the photo detector is given by $\mu_{fso} = (\eta E[I])^f / \sigma_d^2$. For analyzing multiple signals from hybrid links, selection combining (SC) technique is used. In this technique, the link whose received SNR is maximum is selected. The instantaneous SNR for the first hop can be written as

$$\gamma_r = \max(\gamma_{rf}, \gamma_{fso}) \quad (1)$$

III. CHANNEL MODEL

RF link, the FSO link, and the UWOC link channel models considered in the proposed system are discussed in this section.

A. RF Link

If the fading of RF link is taken as Nakagami- m distribution, the SNR of the link will be Gamma distributed whose PDF can be written as [5]

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

Where, m represents the degree of fading in Nakagami- m distribution. The CDF of the SNR of the radio link is given by [5]

$$F_{\gamma_{rf}}(\gamma) = \frac{1}{\Gamma(m)} \gamma\left(m, \frac{m\gamma}{\bar{\gamma}_{rf}}\right) \quad (3)$$

where $\gamma(a, x)$ and $\Gamma(a)$ represent incomplete Gamma function and Gamma function, respectively.

B. FSO Link

FSO link characterized by atmospheric perturbations and misalignment losses which is modeled using DGG fading and Rayleigh distributed misalignment losses. The PDF can be given by [16]

$$f_{\gamma_{fso}}(\gamma) = \frac{A_1}{f\gamma} G_{1, \lambda+\sigma+1}^{\lambda+\sigma+1, 0} \left(A_2 h^{\alpha_2 \lambda} \left(\frac{\gamma}{\mu_{fso}} \right)^{\frac{\alpha_2 \lambda}{f}} \left| \begin{matrix} \tilde{k}_2 \\ \tilde{k}_1 \end{matrix} \right. \right) \quad (4)$$

$$\text{where } A_1 = \frac{\epsilon^2 \sigma \beta_1^{-0.5} \lambda \beta_2^{-0.5} (2\pi)^{1-\frac{(\lambda+\sigma)}{2}}}{\Gamma(\beta_1) \Gamma(\beta_2)}, A_2 = \frac{\beta_1^\sigma \beta_2^\lambda}{\lambda^\lambda \sigma^\sigma \Omega_1^\sigma \Omega_2^\lambda},$$

$$\text{in which } \frac{\lambda}{\sigma} = \frac{\alpha_1}{\alpha_2}, \tilde{k}_1 = \frac{\epsilon^2}{\alpha_2 \lambda}, \Delta(\lambda: \beta_1), \Delta(\sigma: \beta_2), \tilde{k}_2 = \frac{\alpha_2 \lambda + \epsilon^2}{\alpha_2 + \lambda}$$

$$\text{, and } h = \frac{A_1 + B_1}{(1 + \epsilon^2) A_2 \alpha_2 \lambda}, B_1 = \prod_{i=1}^{\sigma+\lambda} \Gamma\left(\frac{1}{\alpha_2 \lambda} + \tilde{k}_{0,i}\right), \tilde{k}_{u,v} \text{ is}$$

$$F_{\gamma_{fso}}(\gamma) = \frac{\epsilon^2 \sigma^{\rho_1 - \nu} \lambda^{\rho_2 - \nu} (\Delta \pi)^+ \quad 2 \quad f^{\rho_1 \tau \rho_1 - \nu}}{\Gamma(a) \Gamma(b)} \times G_{f+1, u+1}^{u, 1} \left(c \left(\frac{\gamma}{\mu_{fso}} \right)^{\alpha_2 \lambda} \left| \begin{matrix} 1, k_3 \\ k_4, 0 \end{matrix} \right. \right) \quad (5)$$

$$\text{in which } u = f(\lambda + \sigma + 1), k_3 = \Delta(f: k_2), k_4 = \Delta(f: k_1), \text{ and } c = \left(\frac{A_2 h^{\sigma_2 \lambda}}{f^{\lambda + \sigma}} \right)^f.$$

C. UWOC Link

The UWOC link is characterized by UOT which is modeled by EGG distribution written as [15]

$$f_{\gamma_u}(\gamma) = \frac{\omega}{f\gamma} G_{0,1}^{1,0} \left(\frac{1}{v} \left(\frac{\gamma}{\mu_{uwoc}} \right)^{\frac{1}{f}} \left| \begin{matrix} - \\ 1 \end{matrix} \right. \right) \frac{c(1-\omega)}{f\gamma \Gamma(a)} G_{0,1}^{1,0} \left(\frac{1}{bc} \left(\frac{\gamma}{\mu_{uwoc}} \right)^{\frac{c}{f}} \left| \begin{matrix} - \\ a \end{matrix} \right. \right) \quad (6)$$

In (6), ω represents the weight of the each distributions in the mixture distribution, such that it value ranges from 0 to 1. Other parameters line a, b, c denote fading level in Generalized Gamma distribution parameters and v denotes Exponential distribution fading level. If c is set as 1, then the mixture PDF gets simplified to Exponential Gamma (EG) distribution which models brininess and bubble concentration for constant temperature [14].

The SNR for UWOC link is given by $\gamma_d = \frac{(\eta d^l d)^f}{\sigma_d^2}$. From instantaneous SNR, the average electrical SNR is computed as, $\mu_{uwoc} = (\eta E[I])^f / \sigma_d^2$. Although average electrical SNR is used for computation and analysis the average SNR of the received optical signal can also be calculated using $\bar{\gamma}_d = (\mu_{uwoc} E[I^f]) / E[I]^f$. Distribution function for γ_d can be given by [15]

$$F_{\gamma_d}(\gamma) = \omega G_{1,2}^{1,1} \left(\frac{1}{v} \left(\frac{\gamma_d}{\mu_{uwoc}} \right)^{\frac{1}{f}} \left| \frac{1}{1,0} \right. \right) + \frac{(1-\omega)}{\Gamma(a)} G_{1,2}^{1,1} \left(\frac{1}{b^c} \left(\frac{\gamma_d}{\mu_{uwoc}} \right)^{\frac{c}{f}} \left| \frac{1}{a,0} \right. \right) \quad (7)$$

IV. STATISTICAL PROPERTIES OF THE SYSTEM SNR

This section explains the statistical properties for instantaneous system SNR of hybrid RF/FSO communication system cascaded with UWOC link using a DF relay. From (1), for SC combining technique, CDF of the SNR for the first hop, i.e., hybrid RF/FSO link is given by

$$F_{\gamma_r} = F_{\gamma_{fso}} F_{\gamma_{rf}} \quad (8)$$

Substituting (3) and (5) in (1), final expression of CDF can be given by

$$F_{\gamma_r}(\gamma) = A_1 G_{f+1,u+1}^{u,1} \left(c \left(\frac{\gamma}{\mu_{fso}} \right)^{\alpha_2 \lambda} \left| \frac{1, k_3}{k_4, 0} \right. \right) \gamma \left(m, \frac{m, \gamma}{\bar{\gamma}_{rf}} \right), \quad (9)$$

where

$$A_1 = \frac{\epsilon^2 \sigma^{\beta_1 - 0.5} \lambda^{\beta_2 - 0.5} (2\pi)^{1 - \frac{f(\lambda + \sigma)}{2}} f^{\beta_1 + \beta_2 - 2}}{\alpha_2 \lambda \Gamma(\beta_1) \Gamma(\beta_2)}$$

Using (9), i.e., CDF of the SNR of the first hop, the end-to-end system SNR can be expressed as

$$\gamma_{eq} = \min(\gamma_r, \gamma_d) \quad (10)$$

Using (10), the CDF for system SNR is written as

$$F_{\gamma_{eq}} = 1 - (1 - F_{\gamma_r})(1 - F_{\gamma_d}) \quad (11)$$

Substituting (9) and (7) in (11), CDF for SNR of the complete two-hop system S can be obtained as

TABLE I:

DGG Distribution Parameters representing variation in Strong and Moderate Irradiance System[16]

Turbulence	α_1	α_2	λ	β_1	β_2	σ	ω_2	ω_1
Strong	1.8621	1	17	0.5	1.8	9	1.5074	1
Moderate	2.1690	1	28	0.55	13	2.35	1.5793	1

$$F_{\gamma_{eq}} = 1 - \left[1 - A_1 G_{f+1,u+1}^{u,1} \left(c \left(\frac{\gamma}{\mu_{fso}} \right)^{\alpha_2 \lambda} \left| \frac{1, k_3}{k_4, 0} \right. \right) \gamma \left(m, \frac{m, \gamma}{\bar{\gamma}_{rf}} \right) \right] \times \left[\omega G_{1,2}^{1,1} \left(\frac{1}{v} \left(\frac{\gamma}{\mu_{uwoc}} \right)^{\frac{1}{f}} \left| \frac{1}{1,0} \right. \right) + \frac{1-\omega}{\Gamma(a)\Gamma} G_{1,2}^{1,1} \left(\frac{1}{b^c} \left(\frac{\gamma}{\mu_{uwoc}} \right)^{\frac{c}{f}} \left| \frac{1}{a,0} \right. \right) \right] \quad (12)$$

From (11), the PDF of the entire system is given as

$$f_{\gamma_{eq}} = f_{\gamma_{rf}}(\gamma) F_{\gamma_{fso}}(\gamma) + f_{\gamma_{fso}}(\gamma) F_{\gamma_{rf}}(\gamma) + f_{\gamma_d}(\gamma) - F_{\gamma_{fso}}(\gamma) + f_{\gamma_{fso}}(\gamma) F_{\gamma_{rf}}(\gamma) + F_{\gamma_{rf}}(\gamma) F_{\gamma_{fso}}(\gamma) f_{\gamma_d}(\gamma) \quad (13)$$

By substituting (2), (3), (4), (5), (6), and (7) in (13), PDF of the full two-hop system SNR can be expressed.

V. PERFORMANCE ANALYSIS

Analytical expression for outage analysis of decode-and-forward based RF/FSO-UWOC cascaded system is presented. For a predetermined threshold value represented by γ_{th} , probability of outage can be written as

$$P_{out}(\gamma_{th}) = \Pr[\gamma_{eq} < \gamma_{th}] = F_{\gamma_{eq}}(\gamma_{th}), \quad (14)$$

Using (12), the P_{out} for γ_{th} can be given by

$$P_{out}(\gamma_{th}) = 1 - \left[1 - A_1 G_{f+1,u+1}^{u,1} \left(c \left(\frac{\gamma_{th}}{\mu_{fso}} \right)^{\alpha_2 \lambda} \left| \frac{1, k_3}{k_4, 0} \right. \right) \gamma \left(m, \frac{m, \gamma_{th}}{\bar{\gamma}_{rf}} \right) \right] \times \left[\omega G_{1,2}^{1,1} \left(\frac{1}{v} \left(\frac{\gamma_{th}}{\mu_{uwoc}} \right)^{\frac{1}{f}} \left| \frac{1}{1,0} \right. \right) + \frac{1-\omega}{\Gamma(a)\Gamma} G_{1,2}^{1,1} \left(\frac{1}{b^c} \left(\frac{\gamma_{th}}{\mu_{uwoc}} \right)^{\frac{c}{f}} \left| \frac{1}{a,0} \right. \right) \right]. \quad (15)$$

TABLE II:

EGG Distribution Parameters for various Air Bubbles Concentration (L/MIN), Thermal Fluctuations ($^{\circ}\text{C}/\text{cm}$) and Irradiance Index σ_1^2 for UWOC link [12]

B L	ΔT	σ_1^2	a	ω	b	λ	c
2.4	0.05	0.148	1.4299	0.2130	1.1817	0.32	17.198
		4				91	4
4.7	0.05	0.420	1.0421	0.4589	1.57768	0.34	35.950
		1				49	1
2.4	0.10	0.165	0.6020	0.2108	1.2795	0.26	21.121
		9				94	1
4.7	0.15	0.476	0.3008	0.4539	1.7053	0.27	54.142
		9				44	2

TABLE III:

EGG Distribution Parameters for various Air Bubbles Concentration and Different Salinity in UWOC Link [12]

Salinity	BL	σ_1^2	ω	λ	a	b	c
Salty	2.4	0.101	0.177	0.469	0.774	1.137	49.177
Fresh	2.4	0.109	0.195	0.527	3.729	1.072	30.321
Salty	4.7	0.131	0.206	0.395	0.531	1.215	35.737
Fresh	4.7	0.123	0.211	0.460	1.253	1.150	41.326

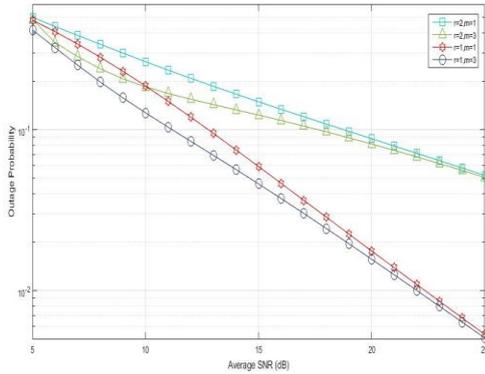


Fig. 2. Outage Probability versus SNR for proposed system using both detection techniques for various RF fading scenarios.

VI. RESULTS

Here numerical results of probability of outage for RF/FSOUWOC system are presented. Results are obtained for various channel parameters of FSO, RF, and UWOC links. Terrestrial optical link DGG distribution parameters taken for system simulation are enlisted in Table I. EGG distribution parameters for UWOC link are given in Table II and Table III.

Fig. 2. presents outage analysis for the considered DF based system, for different Nakagami- m fading parameter, $m = 1$ and 3 and for direct detection and heterodyne detection techniques. From the figure it is seen that stronger the fading, higher is the outage probability. Also the proposed system performs better where heterodyne detection is used as compared to when direct detection and heterodyne detection techniques.

From Fig. 3. outage analysis for different DGG distributed fading parameters for terrestrial optical link is presented. The misalignment loss is kept constant, i.e., $\epsilon = 1.2$. Using parameters given in Table I, the graph shows that lower the irradiance, lower is the outage probability, thus resulting in better outage performance.

In Fig. 4. outage analysis is performed for various bubble level concentration and brininess. Using parameters in Table III we can see that for strong fading conditions, outage probability is very high and vice versa. This is due to

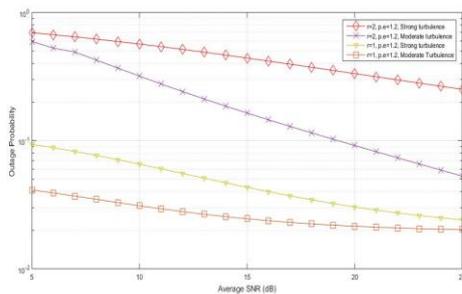


Fig.3. Outage analysis of proposed system for misalignment losses $\epsilon = 1.2$ and different irradiance values.

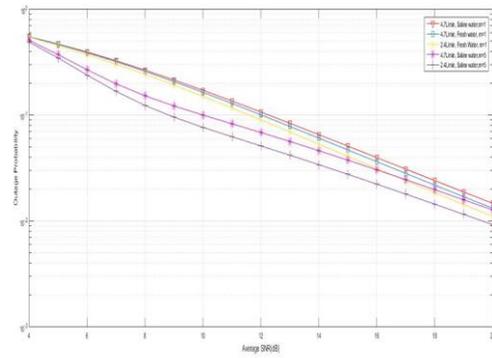


Fig.4. Outage Probability versus SNR for proposed system considering various bubble levels and salinity.

the fact that increase in air bubbles concentration in water increases the UOT which in turn increases the outage probability. It can also be inferred from the figure that higher the brininess of the water source, higher will be the outage probability of the system. Fig.5 shows the outage probability under heterodyne detection techniques under varying temperature gradients and fading parameters listed in Table II. Figure shows that system provides lesser outage at lesser temperature gradients and vice versa.

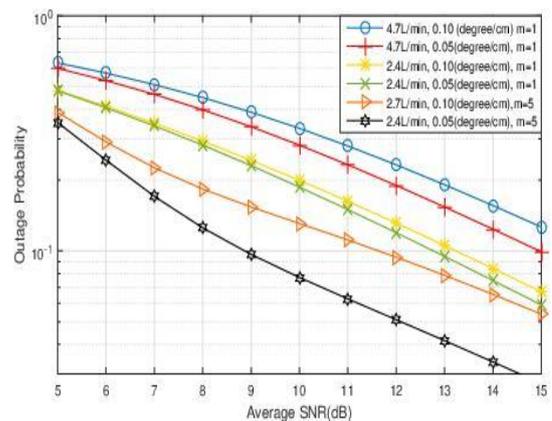


Fig. 5. Outage Probability of proposed system for different temperature gradient and fading.

VII. CONCLUSION

In this paper, hybrid RF/FSO-UWOC cascaded system is presented, using decoding and then forwarding relay, authors have got expressions of (i) statistical characteristics of ratio of signal to noise for the first hop, i.e., hybrid RF/FSO link (ii) statistical characteristics of ratio of signal to noise for complete system (iii) Outage probability. A detailed outage analysis for various channel parameters is performed, which shows that outage probability is severely affected from RF fading parameter, DGG irradiance parameters, and bubble level concentration, temperature gradient and brininess under water.

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