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Asymmetric Satellite-Underwater Visible Light Communication System for Oceanic Monitoring

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ABSTRACT In this paper, we investigate the performance of the proposed oceanic monitoring system that connects the oceanic life with the terrestrial life. For continuous real-time monitoring and ubiquitous coverage, the communication system is aided with a satellite link. Multiple sensor nodes (SN) are deployed at different water levels that collect sensor data and transmit it to underwater vehicles (UV) using underwater visible light communication (UVLC). The UVLC system provides higher data rates at lower latency as compared to existing radio frequency (RF) and acoustic wave alternative for underwater communication (UWC). The UWC system comprises of horizontal haul (HH) and vertical haul (VH) UVLC links modelled using turbulence induced fading. The vertical haul links are modelled as the concatenation of successive non-mixing turbulent links to take into account the change of turbulence with the change of water level. The UVs and submarines communicate with the floating vessels (FVs) using vertical haul UVLC link. The UVs collect the data from the low power sensor nodes and offloads it to the FVs, which further beams it to the satellite on the RF carriers. The novel expressions of performance metrics such as outage probability and average bit error rate are derived. Further, the performance of the system is analysed for various system and channel parameters to prove the feasibility of the proposed communication system.

INDEX TERMS Shadowed Rician, underwater visible light communication, multi-hop relayed system.

I. INTRODUCTION

There has been an expansion of human activities in the marine environment for numerous reasons such as maritime archaeology, monitoring of oceanic ecosystem, underwater scientific data collection and tactical surveillance. Oceanic monitoring systems are of great importance as coasts and aquatic ecosystems are undergoing great changes caused by increasing greenhouse gases, coastal pollution, coastal development or increasing population pressure. The research in the underwater scenario is highly challenging owing to the hostile environment for information transmission. Also, most of the pervasive systems used to perform underwater communication and detection of high-risk events in the sea like Tsunamis or oil spills, need to count on the real time communication. This requirement of an effective underwater communication system and real-time monitoring system has triggered an increase in demand for reliable high data rate underwater wireless communication (UWC).

The severe marine conditions such as absorption, turbulence, and scattering pose extreme challenges for UWC and limit the maximum attainable communication ranges. In the literature acoustic wave communication (AWC), radio frequency (RF) and the optical wave have been adopted for

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carrying out communication in underwater scenarios. The AWC suffers from various impairments like scattering, high propagation delays, high attenuation, low bandwidth, low data rates and also it is harmful to the aquatic mammals and fishes. On the other hand, the RF-based UWC is mostly limited to the shallow areas of water bodies and suffers from high attenuation. The RF waves including microwaves suffer from extreme attenuation. e.g., a 2.4 GHz wave suffers a serious attenuation of 169 dB/m and 189 dB/m in the ocean and fresh water, respectively [1]. Thus, the underwater optical wireless communication is an alternative approach to combat the limitations of low bandwidth and low data rate in the underwater scenario and provides an effective solution for the requirements of low latency and power efficiency for UWC.

In the recent past, tremendous growth has been observed in the research work related to the underwater optical wireless communication [2]. It is apparent through several pieces of research that, the water is relatively transparent to blue and green wavelength and thus optical spectrum from 450 nm to 550 nm can be effectively used for UOWC system. Since the above-mentioned spectrum lies in the visible light range it is more appropriate to term it as underwater visible light communication (UVLC) system. The UVLC system provides high-speed data connection with low latencies and high physical layer security and thus can serve for both monitorings as well as communication. However, the UVLC suffers from severe impairments like absorption, scattering, and turbulence induced fading incurred due to the harshness of the underwater scenario.

In literature, a comprehensive study has been done in order to model the attenuation and turbulence effect of underwater medium on the optical carriers. Most of the studies take into account the atmospheric turbulence models for modeling the underwater scenarios considering the fact that optical turbulence is similar to both the scenarios. To characterize the irradiance fluctuations caused by the turbulence of water, authors in [3] have proposed the log-normal turbulence model. In [4], the authors have considered the assumption of fixed turbulence strength. In [5], the authors proposed Exponential-Gamma model which characterizes the UOWC in the presence of air bubbles over both salty and fresh water. In [6], it is seen that turbulence strength changes through transmission levels as water with different salinity and temperature value form non-mixing layers. In [7], authors have statistically characterized the turbulence induced fading taking into consideration the depth dependency. The vertical channel was modeled using cascaded independent non-identically distributed (i.n.i.d) Gamma-Gamma channel coefficients.

The real-time communication-based monitoring system will be feasible only if the underwater communication system can be connected to the terrestrial communication system through RF links, which is possible using the dual hop cooperative protocol. In [8], authors have evaluated the secrecy performance of a amplify and forward (AF) relay assisted dual hop RF/UOWC system. The AF relay also leads to noise amplification and thus can be replaced by decode and forward (DF) relay for better performance.

The underwater optical wireless communication system achieves high-speed real-time transmission but at the cost of the maximum achievable distance for a single hop underwater transmission. This necessitates the deployment of relays to extend the transmission range. In [9], the authors have proposed an energy efficient relay path selection algorithm for a multi-hop underwater acoustic local area network (LAN). The proposed algorithm increases the network lifetime however, no information about system error performance was presented. Also, the frequencies used in underwater acoustic communication (UAC), overlap with the frequencies of cetacean communication, hence can be harmful to marine mammals. To make UAC an environment-friendly communication system, authors in [10], have proposed a dolphin aware data transmission for multi-hop UAC. In [11], a multi-hop UAC system consisting of equidistant relay transceivers was analyzed over various system impairments. The authors determine the minimum number of hops required to cater to the desired data rate. The UAC suffers from large propagation delay and high signal attenuation thus is not a viable solution for high-speed data service in underwater scenarios. In [12], authors characterized the performance of relay-assisted UOWC system over a log normal channel for turbulence. In [13], authors have implemented detect-and-forward and amplify-and-forward relaying technique in underwater visible light communication. An optimal relay placement was determined to reduce the BER of the system. The authors in [14], proposed a DF relay assisted UOWC system to extend the transmission range and improve the reliability. After going through the literature available in the field of multi-hop oceanic communication system it can be seen that none of the proposed systems account for high turbulence scenario in UOWC and none of the proposed systems connects the oceanic system to the terrestrial system via satellite link. This motivated us to propose a multi-hop oceanic monitoring system that is linked to the terrestrial world via satellite link irrespective of its deployment location.

In this paper, we have proposed the analysis of a novel satellite assisted UVLC system for real-time oceanic monitoring and communication services. The system consists of a bed of sensor nodes (SNs), underwater vehicles (UVs), floating vessels (FVs) and low earth orbit (LEO) satellite. The SNs collect different measurements and transmit them to the in-range UVs, that relay the data to the FVs. The FVs assisted by DF relay retransmits the data to the satellite, which may be broadcasted globally for further processing. The FVs are assumed to be equipped with two-way relay (TWR) for serving submarines with half duplex communication services at the high data rate. Here, we perform the analysis of the considered system, in particular, we first derive statistics of signal to noise ratio (SNR) of the vertical haul UVLC, where the vertical link is modeled as the concatenation of multiple non-mixing layers, taking into account the turbulence induced fading as in [7]. To provide a better insight into the proposed system we have divided it into two functional subsystems namely: 1) TWR based RF/UVLC half-duplex communication system and 2) Multihop oceanic monitoring system. We evaluate the performance of both the subsystems in terms of outage probability and average bit error rate (BER). Further, we analyze the performance of the system for various underwater and oceanic scenarios.

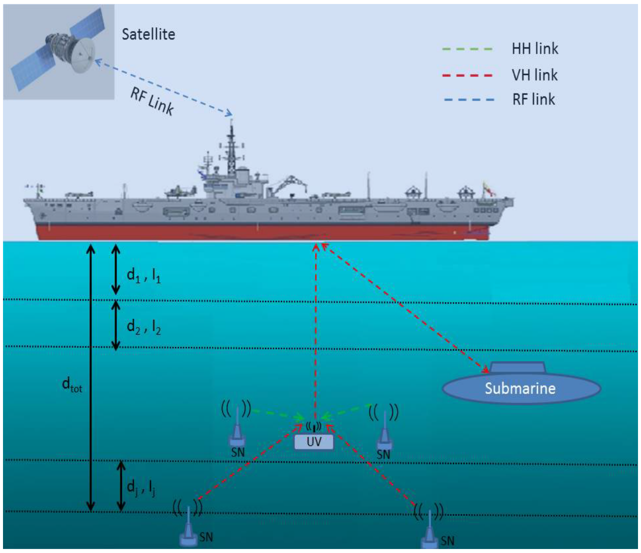

FIGURE 1. **Functional block diagram representation of hybrid RF/UVLC system.**

II. SYSTEM MODEL

In this paper, we propose the analysis of an asymmetric satellite-UVLC system for two possible scenarios: 1) TWR based half duplex communication model, 2) Multihop relay based oceanic monitoring model. Figure 1, shows the composite functional system model for both the considered systems. The system comprises of a) SNs to collect various data of the marine ecosystems b) UVs i.e. augmented underwater vehicles and submarines to acquire data from low powered SNs and communicate with the on-surface devices and c) FVs that are available on the surface of water consists of TWR based DF relay and RF transmitters to communicate directly with the satellite. Based on the turbulence strength, we have classified the UVLC link into two hauls namely horizontal haul (HH) linking terminals at the same water level and vertical haul (VH) linking terminals at different levels. The system description is given as below:

A. TWR BASED HALF DUPLEX COMMUNICATION SYSTEM

This system is proposed to serve the purpose of low latency communication between the submarines or divers and the outside world. The system will be working in half duplex mode using the TWR deployed on the FVs. This is useful for transferring vital military information to the satellite and getting geographical coordinates from the satellites.

The communication between the satellite and submarines is established in two phases. In the first phase known as Mac phase both the terminals transmit their data to the relay. Further, at the relay node, the data is decoded and exclusive ORed (XOR) with each other. In the second step or the broadcast phase, the XORed data is broadcasted to both the terminals. The received data at each terminal is detected and XORed with transmitted data to retrieve back the data transmitted by the other terminal.

B. MULTIHOP OCEANIC MONITORING SYSTEM

Figure 1, shows the deployment of SNs at different water levels in salty or freshwater bodies. The SNs gather various measurements and transmits it to the UVs because of the power limitations. The UVs collect data from the low power SNs and relay it to the FVs. The FVs then decodes the signal and re-transmits the received data from UVs to the satellite on RF carriers.

III. CHANNEL MODEL

This section deals with the detailed description of the channel model considered for analysis of the proposed system. In [16], various statistical models for narrow-band landasatellite (LS) channels are studied, based on which it is assumed that Shadowed-Rician fading provides an excellent fit with measurement data for wide range of conditions. Thus, we consider shadowed Rician fading channel for modeling the satellite to FV link, while the underwater link is subjected to concatenated multiplicative turbulence effect.

A. RF CHANNEL MODEL

In this work, the satellite-FV links are modeled as Shadowed-Rician fading distribution [16]. The probability density function (PDF) of the instantaneous SNR for the same is given as

$$f_{\gamma_{s,fv}}(\gamma)=\frac{\alpha_i}{2b_i\bar{\gamma}_{s,fv}}\exp\left(-\frac{\gamma}{2b_i\bar{\gamma}_{s,bs}}\right)\,{}_1F_1\left(m_i;1;\frac{\beta_i\gamma}{\bar{\gamma}_{s,fv}}\right),\quad (1)$$

where $\alpha_i = \left(\frac{2b_i m_i}{2b_i m_i+\Omega_i}\right)^{m_i}$ and $\beta_i = \frac{\Omega_i}{2b_i(2b_i m_i+\Omega_i)}$. Here, $2b_i$ and Ω_i denotes the average power of multipath component and line-of-sight (LOS) component, respectively and m_i is the Nakagami fading severity factor. The operator ${}_1F_1(\cdot;\cdot;\cdot)$ represents the confluent hypergeometric function. Further, it can be seen that there is a dependence of shadowed-Rician fading links parameter on the elevation angle θ_i as in [16] as,

$$\begin{aligned}b_i &= -4.7943\times10^{-8}\times\theta_i^3+5.5784\times10^{-6}\times\theta_i^2\\&\quad-2.1344\times10^{-4}\times\theta_i+3.2710\times10^{-2},\\m_i &= 6.3739\times10^{-5}\times\theta_i^3+5.8533\times10^{-4}\times\theta_i^2\\&\quad-1.5973\times10^{-1}\times\theta_i+3.5156,\\\Omega_i &= 1.4428\times10^{-5}\times\theta_i^3-2.3798\times10^{-3}\times\theta_i^2\\&\quad+1.2702\times10^{-1}\times\theta_i-1.4864.\end{aligned}$$

TABLE 1. **Parameter of the satellite RF link.**

Shadowing	m_i	b_i	Ω_i
Infrequent light shadowing	19.4	0.158	1.29
Average shadowing	10.1	0.126	0.835
Frequent heavy shadowing	0.739	0.063	8.97×10^{-4}

For a fixed θ_i the values of b_i, m_i and Ω_i are given in Table 1 [16] for different shadowing level. Using [17, Eq.(07.20.03.0108.01)], the confluent hypergeometric function can be represented as

$$ {}_1F_1(\epsilon;1;z) = e^{z}L_{\epsilon-1}(-z), \tag{2}$$

where, $L_m^{\alpha}(\cdot)$ is the Laguerre polynomial defined as [18]

$$L_m^{\alpha}(x) = \sum_{k=0}^{m}(-1)^k\binom{m+\alpha}{m-k}\frac{x^k}{k!}. \tag{3}$$

Using (2) and (3), the confluent hypergeometric function in (1) can be expressed as

$$ {}_1F_1\left(m_i;1;\frac{\beta_i\gamma}{\bar{\gamma}_{s,fv}}\right) = e^{\frac{\beta_i\gamma}{\bar{\gamma}_{s,fv}}}\sum_{k=0}^{m_i-1}\frac{1}{k!}\binom{m_i-1}{m_i-k-1}\left(\frac{\beta_i\gamma}{\bar{\gamma}_{s,fv}}\right)^k. \tag{4}$$

Further substituting (4) in (1) the PDF of shadowed Rician channel can be expressed as

$$f_{\gamma_{s,fv}}(\gamma) = \frac{\alpha_i}{2b_i\bar{\gamma}_{s,fv}}exp\left(-\frac{m_i\gamma}{(2b_im_i+\Omega_i)\bar{\gamma}_{s,fv}}\right) \times\sum_{k=0}^{m_i-1}\frac{1}{k!}\binom{m_i-1}{m_i-k-1}\left(\frac{\beta_i\gamma}{\bar{\gamma}_{s,fv}}\right)^k \tag{5}$$

Subsequently by integrating (5) w.r.t γ, the CDF of the instantaneous SNR can be derived as,

$$\mathcal{F}_{\gamma_{s,fv}}(\gamma) = 1-\frac{\Lambda e^{-\vartheta\gamma}}{\vartheta}\sum_{k=0}^{m_i-1}\left(\frac{\kappa}{\vartheta}\right)^k L_{m_i-k-1}^{k}(-\kappa\gamma), \tag{6}$$

where, $\Lambda = \frac{1}{2b_i\bar{\gamma}}\left(\frac{2b_im_i}{2b_im_i+\Omega_i}\right)^{m_i}$, $\vartheta = \frac{m_i}{(2b_im_i+\Omega_i)\bar{\gamma}}$ and $\kappa = \frac{\Omega_i}{2b_i(2b_im_i+\Omega_i)}$.

B. UNDERWATER VISIBLE LIGHT COMMUNICATION CHANNEL MODEL

The vertical underwater links are modeled as the concatenation of successive non-mixing turbulent links. The total distance between the FV and UV is given as $d_{fv,uv} = \sum_{j=1}^{J} d_j$, where, d_j denotes the thickness of j_{th} water layer as shown in Figure 1. The fading coefficient associated with different layers are modelled as i.n.i.d Gamma-Gamma random variables and the total fading is given as $I_{fv,uv} = \prod_{j=1}^{J} I_j$ where I_j denotes the multiplicative fading coefficient. The PDF of I_j is given as in [7] as

$$f_{I_j}(I_j) = \frac{\alpha_j\beta_j}{\Gamma(\alpha_j)\Gamma(\beta_j)}\mathcal{G}_{0,2}^{2,0}\left[\alpha_j\beta_jI_j\left|{}^{\cdots}_{\alpha_j-1,\beta_j-1}\right.\right], \tag{7}$$

where, α_j and β_j are respectively the effective number of large scale and small scale cells of the scattering process for the j^{th} layer and are defined in [2]. Here, $\mathcal{G}(\cdot)$ is the Meijer-G function. In order to derive the composite PDF of J layered water column, we start by deriving for a two later case i.e. PDF of $I_{SD} = I_1I_2$ and then apply mathematical induction method to derive generalized expression. For two layer water column, the PDF expression is derived using the standard function for joint probability of i.n.i.d variables given as in [15] as

$$f_{I_{fv,uv}}(I_{fv,uv}) = \int_{-\infty}^{\infty} f_{I_1}(I_1)f_{I_2}\left(\frac{I_{fv,uv}}{I_1}\right)|I_1|^{-1}dI_1 \tag{8}$$

Substituting (7) in (8) and using the identity [19, Eq. (2.24.3.1)] we get the PDF for J = 2 case as

$$f_{I_{fv,uv}}(I_{fv,uv}) = \frac{\alpha_1\alpha_2\beta_1\beta_2}{\Gamma(\alpha_1)\Gamma(\alpha_2)\Gamma(\beta_1)\Gamma(\beta_2)} \times\mathcal{G}_{0,4}^{4,0}\left[\alpha_1\alpha_2\beta_1\beta_2I_{fv,uv}\left|{}^{\cdots}_{\alpha_1-1,\alpha_2-1,\beta_1-1,\beta_2-1}\right.\right] \tag{9}$$

Further, the composite PDF of generalized J layer water column is derived by applying mathematical induction method on the derived statistics for single and double layer case and is given as in [7] as,

$$f_{I_{fv,uv}}(I_{fv,uv}) = \frac{\prod_{j=1}^{J}(\alpha_j\beta_j)}{\prod_{j=1}^{J}(\Gamma(\alpha_j)\Gamma(\beta_j))} \times\mathcal{G}_{0,2J}^{2J,0}\left[\prod_{j=1}^{J}(\alpha_j\beta_j)I_{fv,uv}\left|{}^{\cdots}_{\alpha_1-1,\ldots,\alpha_j-1,\beta_1-1,\ldots,\beta_j-1}\right.\right] \tag{10}$$

The instantaneous electrical SNR according to [20] can be defined as $\gamma = (\rho I)^2/N_o$ and average electrical SNR is stated as $\bar{\gamma} = (\rho E[I])^2/N_o$, where, $E[\cdot]$ is the expectation operator and ρ being the optical to electrical conversion efficiency. Considering $E[I] = 1$, since I is normalized to unity and hence $\gamma = \bar{\gamma}I^2$. The PDF of SNR can be derived using the change of variable method in (10) as,

$$f_{\gamma_{fv,uv}}(\gamma) = \frac{\prod_{j=1}^{J}(\alpha_j\beta_j)\gamma^{-\frac{1}{2}}}{\prod_{j=1}^{J}(\Gamma(\alpha_j)\Gamma(\beta_j))2\bar{\gamma}_{fv,uv}^{\frac{1}{2}}} \times\mathcal{G}_{0,2J}^{2J,0}\left[\prod_{j=1}^{J}(\alpha_j\beta_j)\left(\frac{\gamma}{\bar{\gamma}_{fv,uv}}\right)^{\frac{1}{2}}\left|{}^{\cdots}_{\alpha_1-1,\ldots,\alpha_j-1,\beta_1-1,\ldots,\beta_j-1}\right.\right] \tag{11}$$

Further, we derive an expression of the CDF of instantaneous SNR of VH-UVLC link as

$$\mathcal{F}_{\gamma_{fv,uv}}(\gamma) = \int_0^{\gamma} f_{\gamma_{fv,uv}}(\gamma)d\gamma. \tag{12}$$

Substituting (11) in (12) and using the identity [19, Eq.(2.24.2.2)], we get

$$\mathcal{F}_{\gamma_{fv,uv}}(\gamma) = \frac{\prod_{j=1}^{J}(\alpha_j\beta_j)\gamma^{\frac{1}{2}}2^{\mu-1}}{\prod_{j=1}^{J}(\Gamma(\alpha_j)\Gamma(\beta_j))\bar{\gamma}_{fv,uv}^{\frac{1}{2}}(2\pi)^J} \times \mathcal{G}_{1,4J+1}^{4J,1}\left[\prod_{j=1}^{J}(\alpha_j\beta_j)^2\left(\frac{\gamma}{2^{4J}\bar{\gamma}_{fv,uv}}\right)\middle|_{X}^{0.5}\right], \quad (13)$$

where, $X = \frac{\alpha_1-1}{2}, \frac{\alpha_1}{2}\ldots, \frac{\alpha_J-1}{2}, \frac{\alpha_J}{2}, \frac{\beta_1-1}{2}, \frac{\beta_1}{2}\ldots, \frac{\beta_J-1}{2}, \frac{\beta_J}{2}, -0.5$ and $\mu = \sum_{j=1}^{J}(\alpha_j+\beta_j) - 3J + 1$.

IV. PERFORMANCE ANALYSIS OF TWR BASED HALF DUPLEX COMMUNICATION SYSTEM

In this section, we present the performance analysis of the TWR based half duplex communication system in terms of outage probability and average BER.

A. OUTAGE PROBABILITY

In this paper, we have labelled a situation as an outage when the instantaneous SNR of the complete system falls below a desired threshold (γ_{thres}). For a TWR assisted submarine to satellite system, the outage probability is expressed as in [8] as,

$$P_{out_{DH}} = \Pr[\min(\gamma_{s,fv}, \gamma_{fv,uv}) < \gamma_{thres}]. \quad (14)$$

Assuming both the links to be independent we can rewrite (14) as

$$P_{out_{DH}} = \mathcal{F}_{\gamma_{s,fv}}(\gamma_{thres}) + \mathcal{F}_{\gamma_{fv,uv}}(\gamma_{thres}) - \mathcal{F}_{\gamma_{s,fv}}(\gamma_{thres})\mathcal{F}_{\gamma_{fv,uv}}(\gamma_{thres}). \quad (15)$$

Substituting (6) and (13) in (15), the novel expression for outage probability is given as in (16), as shown at the bottom of this page.

B. AVERAGE BIT ERROR RATE

An average BER is required to analyze the effects of fading or turbulence and also the use of different modulations. In the proposed system, we have analyzed the system for different modulation schemes for the satellite to base station RF link, while the UVLC link is assumed to be On-Off Keying (OOK) modulated. The average BER of RF link is calculated for a list of binary digital carrier modulation and is expressed as in [21], as

$$\mathcal{P}_e = \frac{1}{2\Gamma(s)}\int_0^{\infty}\Gamma(s, t\gamma)f_{\gamma}(\gamma)d\gamma, \quad (17)$$

where, the constants s and t denote different modulation schemes as given in [21] as Table 1.

TABLE 2. **Different binary modulation schemes.**

Modulation Scheme	s	t
Binary-PSK	0.5	1
Differential-PSK	1	1
Binary-Frequency shift keying (BFSK)	0.5	0.5

Utilizing (19) and (5), the BER of satellite to floating base station RF link is derived as

$$\mathcal{P}_{e_{s,fv}} = \frac{\alpha_i}{2b_i\bar{\gamma}_{s,fv}}\sum_{k=0}^{m_i-1}\frac{1}{k!}\binom{m_i-1}{m_i-k-1}\left(\frac{\beta_i}{\bar{\gamma}_{s,fv}}\right)^k \times \vartheta^{-(k+1)}\mathcal{G}_{2,2}^{2,1}\left[\frac{s}{\vartheta}\middle|_{0,t}^{-k,1}\right]. \quad (18)$$

The average BER for UOWC link is calculated considering OOK modulation and is derived using the expression as in [7],

$$\mathcal{P}_s(E;\gamma) = \frac{1}{2}erfc\left(\sqrt{\frac{\gamma}{2}}\right) \quad (19)$$

and

$$P_{e_{fv,uv}} = \frac{1}{2}\int_0^{\infty}P_s(E:\gamma)f_{\gamma_{fv,uv}}(\gamma)d\gamma.$$

where, $erfc$(Âů) denotes the complementary error function. To simplify the integrals replacing $erfc\left(\sqrt{\frac{\gamma}{2}}\right) = \frac{1}{\sqrt{\pi}}\mathcal{G}_{1,2}^{2,0}\left(\frac{\gamma}{2}\middle|_{0,0.5}^{1}\right)$. The final expression for average BER for UOWC link is given as

$$\mathcal{P}_{e_{fv,uv}} = \frac{\prod_{j=1}^{J}(\alpha_j\beta_j)2^{\mu}}{\prod_{j=1}^{J}(\Gamma(\alpha_j)\Gamma(\beta_j))\bar{\gamma}_{fv,uv}^{\frac{1}{2}}(2\pi)^J\sqrt{\pi}} \times \mathcal{G}_{2,4J+1}^{4J,2}\left[\prod_{j=1}^{J}(\alpha_j\beta_j)^2\left(\frac{1}{2^{4J-1}\bar{\gamma}_{fv,uv}}\right)\middle|_{X}^{0.5,0}\right]. \quad (20)$$

For the considered system, an error at the receiver will occur if any one of the link is erroneous. The expression of average BER for the TWR assisted submarine to satellite system is expressed as

$$\mathcal{P}_{e_{DH}} = \mathcal{P}_{e_{s,fv}}(1-\mathcal{P}_{e_{fv,uv}}) + (1-\mathcal{P}_{e_{s,fv}})\mathcal{P}_{e_{fv,uv}}, \quad (21)$$

where, $\mathcal{P}_{e_{s,fv}}$ and $\mathcal{P}_{e_{fv,uv}}$ are independent probabilities of error of S-FV and FV-UV link given in (18) and (20), respectively.

V. PERFORMANCE ANALYSIS OF MULTIHOP OCEANIC MONITORING SYSTEM

In this section, performance evaluation of the multihop oceanic monitoring system is evaluated in terms of outage and average BER.

$$P_{out_{DH}} = 1 - \frac{\Lambda e^{-\vartheta\gamma}}{\vartheta}\sum_{k=0}^{m_i-1}\left(\frac{\kappa}{\vartheta}\right)^k L_{m_i-k-1}^{k}(-\kappa\gamma)\left[1 - \frac{\prod_{j=1}^{J}(\alpha_j\beta_j)\gamma^{\frac{1}{2}}2^{\mu-1}}{\prod_{j=1}^{J}(\Gamma(\alpha_j)\Gamma(\beta_j))\bar{\gamma}_{fv,uv}^{\frac{1}{2}}(2\pi)^J}\mathcal{G}_{1,4J+1}^{4J,1}\left[\prod_{j=1}^{J}(\alpha_j\beta_j)^2\left(\frac{\gamma}{2^{4J}\bar{\gamma}_{fv,uv}}\right)\middle|_{X}^{0.5}\right]\right] \quad (16)$$

A. OUTAGE PROBABILITY

The outage probability for a triple hop system in terms of CDF of SNR is expressed as

$$P_{out_{TH}} = \Pr[\min(\gamma_{s,fv}, \gamma_{fv,uv}), \gamma_{uv,sn}) < \gamma_{thres}], \tag{22}$$

Assuming all the links to be independent we can rewrite (22) as

$$\begin{aligned} P_{out_{TH}} = 1 - (1 - \mathcal{F}_{\gamma_{s,fv}}(\gamma_{thres}))(1 - \mathcal{F}_{\gamma_{fv,uv}}(\gamma_{thres})) \\ \times (1 - \mathcal{F}_{\gamma_{uv,sn}}(\gamma_{thres})). \end{aligned} \tag{23}$$

Substituting (6) and (13) in (15), the novel expression for outage probability is given as in (24), as shown at the bottom of this page. The variables α_d and β_d in (24) are the effective number of large scale and small scale cells of the scattering process for the d^{th} layer that depends on the depth of deployment of SNs and $X_d = \frac{\alpha_d - 1}{2}, \frac{\alpha_d}{2}, \frac{\beta_d - 1}{2}, \frac{\beta_d}{2} \ldots, -0.5$.

B. AVERAGE BER

For the considered triple hop system, an erroneous decoding will occur if any one or all the three receiving relay nodes is erroneous. The expression of average BER for the complete system is given as

$$\begin{aligned} \mathcal{P}_{eTH} &= \mathcal{P}_{e_{s,fv}} \mathcal{P}_{e_{fv,uv}} \mathcal{P}_{e_{uv,sn}} + \mathcal{P}_{e_{s,fv}} (1 - \mathcal{P}_{e_{fv,uv}}) \\ &\quad \times (1 - \mathcal{P}_{e_{uv,sn}}) + (1 - \mathcal{P}_{e_{s,fv}}) \mathcal{P}_{e_{fv,uv}} (1 - \mathcal{P}_{e_{uv,sn}}) \\ &\quad + (1 - \mathcal{P}_{e_{s,fv}})(1 - \mathcal{P}_{e_{fv,uv}}) \mathcal{P}_{e_{uv,sn}}, \end{aligned} \tag{25}$$

where, $\mathcal{P}_{e_{s,fv}}$ and $\mathcal{P}_{e_{fv,uv}}$ are independent probabilities of error of S-FV and FV-UV link given in (18) and (20) respectively. Here $\mathcal{P}_{e_{uv,sn}}$ is the average BER of UV-SN link which is HH-UVLC link. THE UV-SN link is subjected to a single layer turbulence effect and hence can be obtained using (20). The expression for $\mathcal{P}_{e_{uv,sn}}$ is given as

$$\begin{aligned} \mathcal{P}_{e_{uv,sn}} &= \frac{\alpha_d \beta_d 2^{\alpha_d + \beta_d - 2}}{\Gamma(\alpha_d)\Gamma(\beta_d) \bar{\gamma}_{uv,sn}^{\frac{1}{2}} 2\pi \sqrt{\pi}} \\ &\quad \times \mathcal{G}_{2,5}^{4,2} \left[(\alpha_d \beta_d)^2 \left(\frac{1}{8\bar{\gamma}_{uv,sn}} \right) \Bigg|_{X_d}^{0.5,0} \right]. \end{aligned} \tag{26}$$

VI. ANALYTICAL RESULTS

In this section, the analytical results of the proposed system are presented for various atmospheric and underwater scenarios. We have considered the thickness of each layer to be 10 m, thus the depth of 30 m and 40 m corresponds to three and four layers, respectively. The channel parameters for 4-cascaded layers are given as in [7] as $(\alpha_j, \beta_j) = (4.59, 2.82), (4.64, 2.88), (4.70, 2.96)$ and $(4.77, 3.05)$. The average SNR of RF link $\bar{\gamma}_{s,fv}$ is fixed at 30 dB.

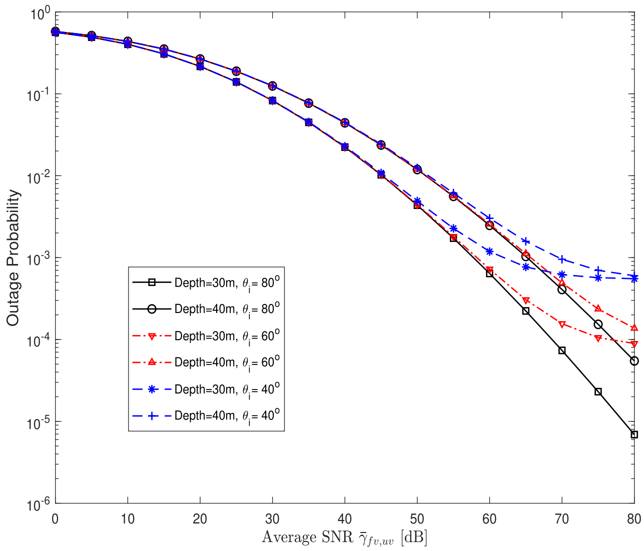

FIGURE 2. Outage Probability versus $\bar{\gamma}_{fv,uv}$ for varying elevation angles of satellite link.

Figure 2 depicts the half duplex TWR system's outage probability versus average SNR of VH-UVLC link ($\bar{\gamma}_{fv,uv}$) for varying elevation angles. The impact of elevation angle can be clearly observed as an increase in the angle leads to a better performance. This is due to the fact that the high elevation angles result in more favourable channel conditions with light shadowing. The results are iterated for varying depth and it is observed that the UVs available at lower depth are more probable of facing outage conditions.

Figure 3 demonstrates the effect of oceanic depth on the underwater system performance for OOK modulation scheme. It can be observed that as the depth of deployment increases the probability of error increases. This is quite intuitive as increase in depth results in increase in turbulence strength owing to the multiplicative turbulence effect which results in higher BER. It can be observed that for the error floor of 10^{-3} the gain of 20 dB is achieved when the depth is reduced from 40m to 10m. Thus UVs are necessary to collect data from deep deployed low powered SNs.

Figure 4 depicts the graph of average BER versus average SNR of VH-UVLC link ($\bar{\gamma}_{fv,uv}$) for cascaded satellite RF link and UVLC link. The performance is examined for varying

$$\begin{aligned} P_{out_{TH}} = 1 - \frac{\Lambda e^{-\vartheta\gamma}}{\vartheta} \sum_{k=0}^{m_i - 1} \left(\frac{\kappa}{\vartheta}\right)^k L_{m_i - k - 1}^{k}(-\kappa\gamma) \left[1 - \frac{\prod_{j=1}^{J} (\alpha_j \beta_j) \gamma^{\frac{1}{2}} 2^{\mu - 1}}{\prod_{j=1}^{J} (\Gamma(\alpha_j)\Gamma(\beta_j)) \bar{\gamma}_{fv,uv}^{\frac{1}{2}} (2\pi)^J} \mathcal{G}_{1,4J+1}^{4J,1} \left[\prod_{j=1}^{J} (\alpha_j \beta_j)^2 \left(\frac{\gamma}{2^{4J} \bar{\gamma}_{fv,uv}} \right) \Bigg|_{X}^{0.5} \right] \right] \\ \times \left[1 - \frac{\alpha_d \beta_d) \gamma^{\frac{1}{2}} 2^{\alpha_d + \beta_d - 3}}{(\Gamma(\alpha_d)\Gamma(\beta_d)) \bar{\gamma}_{uv,sn}^{\frac{1}{2}} (2\pi)} \mathcal{G}_{1,5}^{4,1} \left[(\alpha_d \beta_d)^2 \left(\frac{\gamma}{16\bar{\gamma}_{uv,sn}} \right) \Bigg|_{X_d}^{0.5} \right] \right] \end{aligned} \tag{24}$$

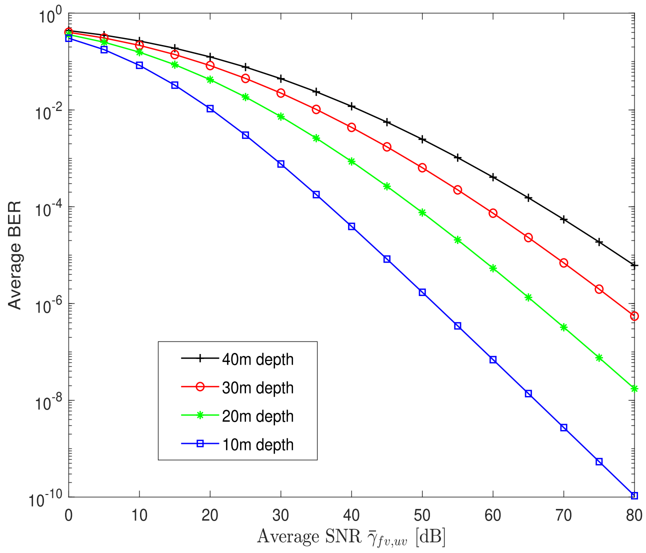

FIGURE 3. Average BER versus $\bar{\gamma}_{fv,uv}$ for UVLC link.

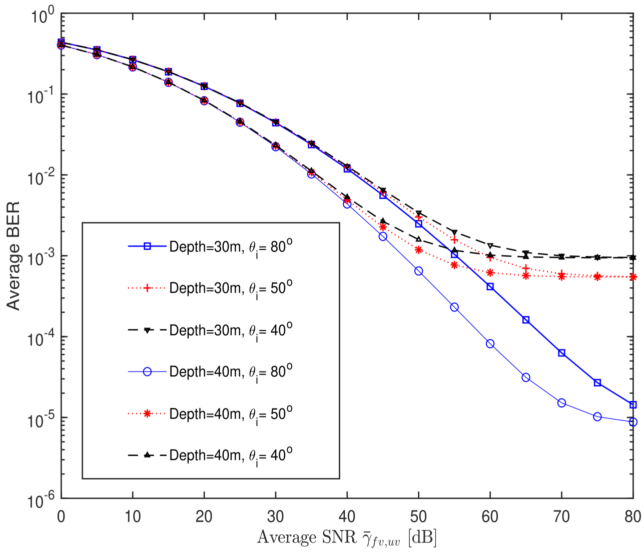

FIGURE 5. Average BER versus $\bar{\gamma}_{fv,uv}$ for VH UVLC - RF link considering different elevation angle.

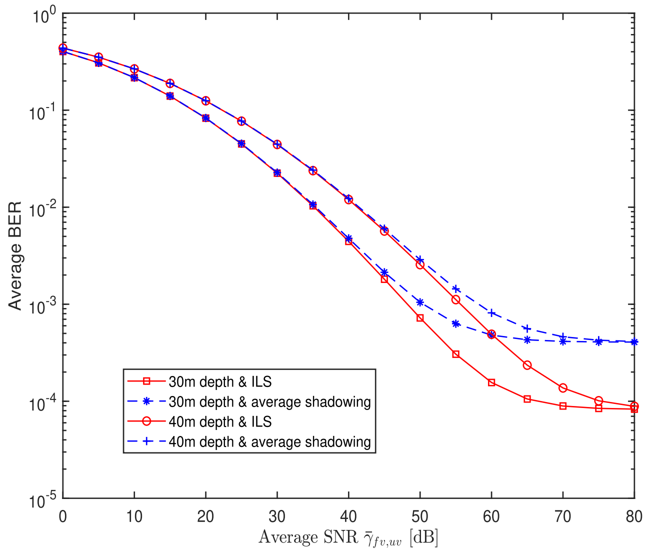

FIGURE 4. Average BER versus $\bar{\gamma}_{fv,uv}$ for VH UVLC - RF link considering different fading severity.

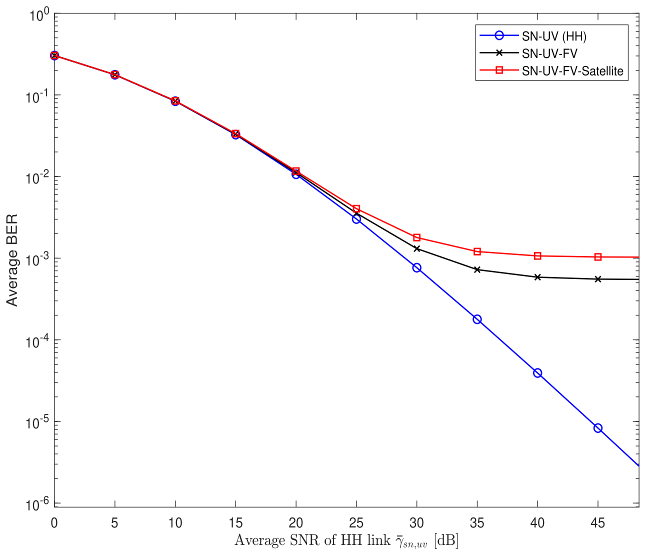

FIGURE 6. Average BER versus $\bar{\gamma}_{sn,uv}$ for HH UVLC - VH UVLC - RF link.

shadowing level and it is clearly seen that the average BER of the system is limited to higher values for higher shadowing probability. It can be seen that for infrequent light shadowing (ILS) system error rate is almost 10 times lesser as compared to average shadowing at $\bar{\gamma}_{fv,uv} = 80$dB.

Figure 5, shows the error probability performance for TWR assisted communication system for serving UVs like submarines. It can be seen that for higher elevation angle error probability is far lesser as compared to lower elevation RF links. The low elevation angle leads to frequent heavy shadowing and thus weak satellite to FV link. This limits the performance of the system and can be improved either by increasing the transmitted power or by increasing θ_i.

Figure 6, demonstrates average BER versus average SNR of HH-UVLC link $\bar{\gamma}_{sn,uv}$ plots for triple hop VH UVLC - HH UVLC - RF system. The plot clearly demonstrates the effect of adding each link. The SNs are assumed to be deployed at a depth of 40m from the surface of water with channel parameter $(\alpha_j, \beta_j) = (4.77, 3.05)$ and UV available at the same depth. The average SNR $\bar{\gamma}_{fv,uv}$ and $\bar{\gamma}_{s,fv}$ are fixed at 30dB.

VII. CONCLUSIONS

In this paper, the novel asymmetric satellite - UVLC system for oceanic monitoring was proposed and its performance was analysed to prove its feasibility. The system performance was iterated for various underwater and atmospheric conditions to study their corresponding effects. The proposed system can serve for collecting different data that can be used for detecting signs of tsunamis, monitoring water ecology, archaeological expeditions and surveying shipwrecks. The proposed system can also serve the submarines with secure link for data transfer and coordinates update. The UVLC system depends on line of sight link hence is prone to blockages by mobile aquatic animals thus future studies will include the effect of blocking on system performance. Further, the DF relay can be replaced by an energy and data buffer aided relay at the surface buoys that will make the proposed system a more greener communication system.

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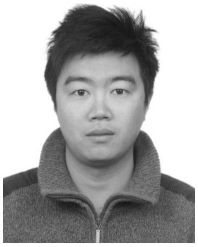

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