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Under-Sea Ice Diffusing Optical Communications

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ABSTRACT In this paper, we propose a novel approach to establish a reliable high-speed broadcast communication link between a group of autonomous underwater vehicles (AUVs) swarm under-sea ice. We utilize the fact that sea ice exists above the AUVs to diffuse the optical beam sent from AUV transmitter. We model this channel using a new seawater-sea ice cascaded layers (SSCL) model in which the vertical channel is divided into multiple layers based on their optical characteristics. The diffusing pattern of the SSCL model is computed using Monte Carlo numerical ray-tracing technique. We derive a quasi-analytic equation for the channel impulse response (CIR) which is valid for AUV receivers with different configurations, locations and orientations. The communication performance of underwater sea ice diffusing system is quantified via bit error rate performance, power penalty and maximum achievable bit rate. Our results reveal that, for a snow-covered sea ice sheet with thickness of 36 cm and bare sea ice sheet with thickness 12 cm, the proposed system can achieve a broadcast communication rate of 100 Mbps with ranges up to 3.5 meters and 3 meters, respectively, with BER less than 10^{-3} and average transmitted power of 100 mW.

INDEX TERMS underwater wireless optical communication, diffusing communication, AUVs, channel impulse response.

I. INTRODUCTION

Sea ice regions are key zones as they play an important role in climate change and ecosystems of the Earth [1]. They cover roughly 7% and 15% of the earth and the sea-waters, respectively. To understand this rapidly changing environment, researchers have been working on measuring campaigns such as mapping thickness of the sea ice sheets and measuring ice characteristics (e.g., the temperature and salinity) [2], [3]. In addition, it is important to observe, monitor, and protect this ecosystem (e.g., detecting and removing oil spills) [4]. Due to their reliability, cost-effectiveness, and ability to improve human safety, autonomous underwater vehicles (AUVs) are commonly used in under sea ice measurements [2]–[4].

A reliable communication link between the AUVs is essential in order for them to work collaboratively to tackle complex tasks, such as the case of cooperative agents in AUV swarms [5]–[7]. For any technologies deployed on AUVs, limitations on the size, weight and power consumption are critical [8]. Acoustic, radio frequency, and optical communi-

cations are the three main wireless communication systems used in underwater purposes. Compared to both acoustic and radio frequency systems, optical wireless communication (OWC) systems achieve higher transmission data-rate, better power efficiency, and smaller size on the order of cubic centimeters [3], [9].

The mobility of the AUVs, the nature of the sea ice terrain, and presence of the marine groups (e.g., bears, seals, penguins) can degrade the performance of line-of-sight (LOS) OWC systems because of high misalignment and blockage probabilities [10], [11]. While, non-line-of-sight (NLOS) links based on omni-directional sources such as light emitted diodes (LEDs) offer relatively higher reliability, they provide relatively lower speed communication due to their limited modulation bandwidth. In indoor environments, broadcast OWC systems have been proposed where the ceiling, walls and floor have been employed as diffuse reflectors of the optical signal [12]. There has been much work on the optimizing of the diffusing pattern, and the system complexity

of such indoor systems to reduce the effects of interference and background noise [13]–[16]. Recently, the application of diffusing communication links to underwater scenarios has started to be considered [9]. Arnon *et al.* [17] and Liu *et al.* [18] proposed using seawater-air interface as reflective surface and turbidity seawaters as scattering mediums for NLOS communications, respectively. Anous *et al.* [19] modeled a vertical underwater link taking into account the in-homogeneous nature of the seawater environment with the depth for both LOS and NLOS scenarios. Anous *et al.* used the concept of the layering to discretize the vertical variation in the temperature and salinity profiles of the seawaters. This discretized modelling approach of using multi-layers representing the vertical variation in the temperature, salinity and pressures profiles is commonplace in such systems and widely used in the geoscience literature (e.g., [20]–[24]).

In this paper, we propose the concept of *sea ice diffusing optical communications* (SDOCs) where the sea ice is utilized as a diffusing surface with a LD source to establish high-speed short-distance broadcast communication links between the AUVs. Link reliability is improved due to the multiple reflections/scattering from the sea ice and thanks to high impurities contaminating ice mediums and snow caps covering the sea ice sheets. To the best knowledge of the authors, this is the first introduction of this approach in the literature. The main contributions in this paper are summarized as follows:

- For the first time, we introduce a new approach in which the ice sheet is utilized as a diffusing surface to establish reliable diffusing-based broadcast link between underwater AUVs.
- The channel is presented using a seawater-sea ice cascaded layers (SSCL) model where the ice and snow are divided into layers according to the variations in their temperature and salinity profiles.
- In order to obtain transmitter to receiver channel impulse response (CIR), we propose a new simulation methodology consisting of two-steps. In the first step, a Monte Carlo numerical ray tracing (MCNRT) method is used to numerically obtain the ice sheet diffusing pattern. In the second step, the CIR is derived analytically considering the configuration, position and orientation of the AUVs. This methodology reduces the computation time of the CIR, where the first step is computed once, regardless of the number of the receivers, while the second step is only repeated for each receiver.
- An appropriate transceiver is proposed by which the SDOC system achieves a high speed and longer communication range with low bit error rate (BER).
- We numerically investigate the CIR for different sea ices, seawater, and receiver configurations. As well, the performance of the SDOC system is evaluated considering the BER, normalized optical power penalty (NOPP), and maximum achievable bit rate.

The balance of the paper is organized as follows. In Section

II, we introduce the SDOC approach and the SSCL channel model. In Section III, we use the MCNRT method to model the upward transmission, then derive a quasi-analytic equation for the CIR. We introduce and model the proposed transceiver architecture in Section IV. In Section V, we numerically investigate the channel characteristics and system performance. Finally, conclusions are given in Section VI.

II. PROPOSED SEA ICE DIFFUSING OPTICAL COMMUNICATION (SDOC) APPROACH

In this section we introduce the SDOC link as a new approach to establish communication between AUVs operating under sea ice. We discuss the temperature and salinity profile of the sea ice. Then, we introduce a new approach to model optical characteristics of the sea ice.

A. SDOC ARCHITECTURE

As shown in Fig. 1, we consider a group of AUVs, for example an AUVs-swarm¹, navigating several meters beneath a sheet of sea ice. The AUVs move together in the coordinated fashion with a separation of a few meters. In the proposed approach a broadcast communication link between the AUV transmitter (AUV-Tx) and the AUV receivers (AUV-Rxs) is accomplished in two steps: upward and downward transmissions. In the upward transmission, the AUV-Tx sends a narrow collimated laser beam toward the sea ice. Due to impurities (particles)², the transmitted beam is subject to intense scattering at the surface and during propagation in the interior of the ice sheet. Inside the sea ice, a portion of the power will be transmitted through the sheet and lost to the atmosphere. Alternatively, the transmitted light may be trapped in the interior of the sheet where it is absorbed. Finally, a portion of the incident light will be diffused back from the ice sheet into the water. This diffused light which escapes the ice sheet is the useful signal which is used to establish the broadcast communication link. Given that the light is diffused inside the sheet, as shown in the green ellipse in Fig. 1, a wide coverage area is possible. The AUV-Tx can control the position of the diffusing spot by adjusting the direction of the laser beam, i.e., polar and azimuthal launching angles. For instance, if the AUV-Rxs are distributed symmetrically around the AUV-Tx, the beam should be vertically oriented toward the ice sheet to offer a fair coverage for all AUV-Rxs, as shown for the case in Fig. 1. However, if the AUV-Rxs are biased to one side, the AUV-Tx can orient its beam toward the direction of the AUV-Rxs to improve link quality. In the downward transmission from the ice sheet, the diffused beam propagates in the seawater and covers the AUV-Rxs with a large spot. Regardless of the position and orientation of the AUV-Rxs, each AUV-Rx receives a portion of this diffused beam, and the AUV-Tx establishes a broadcast communication with the AUV-Rxs.

¹Such a swarm typically employs a number of AUVs, however for simplicity, just five AUVs are shown in Fig. 1.

²In this paper, the term of impurity and particle refer to any of: solid matter, dissolved matter, brine pockets, solid salt, air bubbles or air gaps.

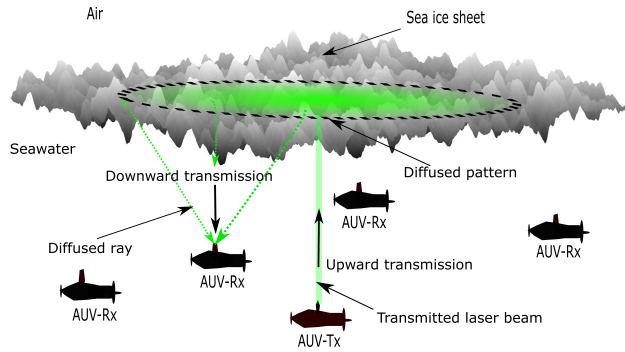


FIGURE 1: A topology for the SDOC approach: AUVs navigate underneath a sea ice and communicate with up and downward transmissions.

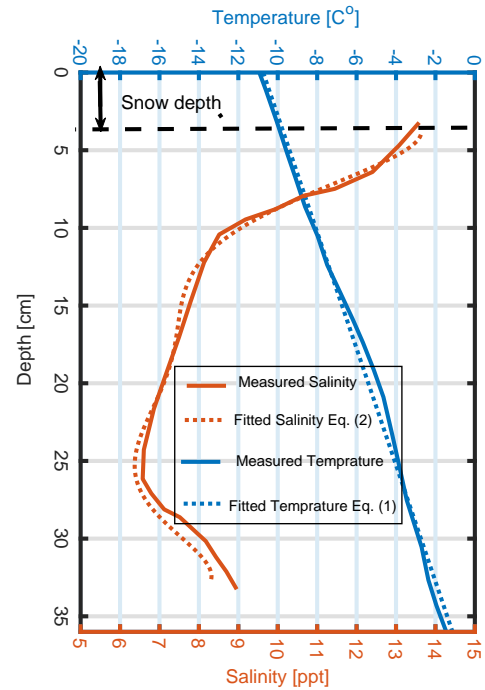


FIGURE 2: The temperature and salinity profiles versus the sea ice depth for a snow-covered sea ice sheet as measured by [27].

144 The intensity of the diffused optical signal that emanates
 145 from the sea ice to the seawater depends on the density of
 146 impurities which contaminate the ice sheet as well as the
 147 sea ice surface roughness. The optical characteristics (e.g.,
 148 absorption and scattering coefficients) of the ice sheet are
 149 highly affected by changes in impurity density which depend
 150 on ice sheet temperature and salinity [25], [26]. Temperature
 151 and salinity affect the freezing process of the sea ice which
 152 can introduce contaminants such as brine pockets, solid salts,
 153 and air bubbles. Given the high values for the temperature
 154 and salinity, the ice is most likely contaminated by particles
 155 and air bubbles [25]. For sea ice covered by snow, optical
 156 properties will be impacted by temperature changes as well
 157 as the gaps between snowflake particles [26].

158 An example of the measured temperature and salinity profiles
 159 shown in Fig. 2. This figure represents the temperature and
 160 salinity of a 36 cm snow-covered sea ice sheet with
 161 3 cm of snow cap and 33 cm of ice. The shown profiles
 162 are measured between November 2007 and June 2008 in
 163 the southern Beaufort Sea–Amundsen Gulf, Canadian Arctic
 164 [27]³. As shown in Fig. 2, the temperature $T(z)$ and salinity
 165 $S(z)$ change with the depth z inside the ice sheet. The two
 166 curves in Fig. 2 can be well fitted by the following equations

$$T(z) = 0.2668z - 10.74, \quad (1)$$

$$S(z) = -3.24 \times 10^{-7}z^6 + 3.58 \times 10^{-5}z^5 - 1.47 \times 10^{-3}z^4 + 2.74 \times 10^{-2}z^3 - 0.205z^2 - 0.095z + 13.63, \quad (2)$$

167 where T is the temperature in Celsius ($^{\circ}C$), S is the
 168 salinity in part per thousand (ppt), and $0 \leq z \leq 36$ cm.
 169 The equations are shown in the figure, and there is good
 170 agreement between the measured and the fitted profiles⁴.

171 Another example is a 12 cm bare-sea ice sheet whose
 172 temperature and salinity profiles are shown in [29, Fig. 3].

³Although the given profiles are for specific ice sheet, they hold the common linear relationship and C-shape for temperature T and salinity S , respectively [28].

⁴The corresponding goodness of the fit criteria are; R-square = {0.9916, 0.9931} for the temperature and salinity curves, respectively.

The sheet is young laboratory-grown saline sea ice. The two profiles of the sheet can be well fitted in $T(z)$ and $S(z)$ functions as⁵

$$T(z) = 1.176z - 15.61, \quad 0 \leq z \leq 12\text{cm} \quad (3)$$

$$S(z) = 0.05003z^2 - 0.7432z + 8.203. \quad (4)$$

176 These two ice sheet examples will be used later in the
 177 numerical results as case studies.

178 As shown in Fig. 2, the top surface of the sea ice is lower
 179 in the temperature than the bottom due to a cooling of the
 180 atmosphere and a warming of the seawater. As well, the
 181 salinity at the top and bottom is much higher than at the
 182 middle of the sea ice sheet. The vertical variations in the
 183 temperature and salinity with the thickness of the ice sheet
 184 result in changes in particle densities, which impact the channel
 185 optical characteristics. Given that the scattering inside the
 186 ice sheet is extensive and varies through the thickness of the
 187 ice sheet, channel modeling is challenging. In the following
 188 we introduce a simplified channel model.

189 B. SEAWATER-SEA ICE CASCADED LAYERS (SSCL) CHANNEL MODEL 190

191 In this subsection, inspired by the geoscience literature [25],
 192 [26], we propose a SSCL channel model for upward trans-

⁵The corresponding goodness of the fit criteria are; R-square = {0.9997, 0.9788} for the temperature and salinity curves, respectively.

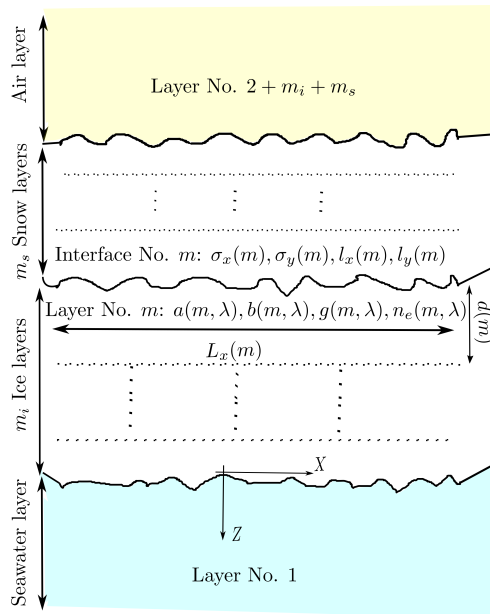


FIGURE 3: The SSCL channel model.

and soot). However, snow layers are composed of air as a hosting medium with a fewer numbers of mixture particles (e.g., snow grains, algal and non-algal particles and soot). Due to these particles, the optical ray propagating inside the m^{th} layer of the SSCL model suffers from absorption and scattering effects. The absorption coefficient, $a(m)$, is the weighted summation of the contribution from the mixture components as [56]

$$a(m) = f_{v_o} a_o(m) + \sum_{j=1}^{J_m} f_{v_j} a_j(m), \quad (5)$$

where a_o and f_{v_o} are the absorption coefficient and the volume fraction of the hosting medium, respectively. As well, a_j and f_{v_j} are the absorption coefficient and the volume fraction associated with the j^{th} particle, respectively, where $f_{v_o} + \sum_{j=1}^{J_m} f_{v_j} = 1$. Symbol J_m is the number of mixture particles in layer m , and the value of J_m depends on the hosting medium of the layers and its surrounding environment. The hosting medium does not contribute to the scattering effect, thus, the scattering coefficients for each layer, $b(m)$, are weighted summations of the contribution from the impurity components only as [56]

$$b(m) = \sum_{j=1}^{J_m} f_{v_j} b_j(m) \quad (6)$$

where b_j is the scattering coefficient associated with the j^{th} particle.

Based on the assumptions given in [26] and [54], the one term Henyey-Greenstein (OTHG) function is a good approximation to the phase scattering function [57]

$$p_{\theta_s}(\theta_s, m) = \frac{1}{4\pi} \frac{1 - g(m)^2}{(1 + g(m)^2 - 2g(m) \cos(\theta_s))^{3/2}}, \quad (7)$$

where $g(m)$ is the asymmetry factor and θ_s is a scattering angle. The asymmetry factor is obtained using the weighted sum as [56]

$$g(m) = \frac{1}{b_m(m)} \sum_{j=1}^{J_m} b_j(m) g_j(m), \quad (8)$$

where g_j is the asymmetry factor of the j^{th} particle. The effective refractive index of the layer is computed using the volume fraction f_{v_j} as [58]

$$n_e(m) = f_{v_o} n_o(m) + \sum_{j=1}^{J_m} f_{v_j} n_j(m), \quad (9)$$

where n_o is the refractive index of the hosting medium, and n_j is the refractive index of the j^{th} particle.

The interfaces between the adjacent layers are assumed to be rough surfaces which leads to optical surface scattering at

193 mission in the SDOC approach. By SSCL, the vertical up-
 194 ward transmission link is modelled using cascaded layers
 195 of the seawater, ice, snow, and the air as shown in Fig. 3.
 196 Each of the layers of seawater and air are presented using a
 197 single layer since in the scale of few meters range, the particle
 198 densities do not change greatly with the depth [21], [22], [30,
 199 Ch. 3]. However, as mentioned in the previous subsection,
 200 the optical characteristics inside the ice sheet change contin-
 201 uously with the depth. Thus, we divide the ice sheet and
 202 snow layers into m_i and m_s of cascaded layers, respectively,
 203 over which the temperature and salinity are approximated as
 204 being uniform and presented using the average temperature
 205 $T(m)$ and average salinity $S(m)$. The thickness of each layer
 206 (and consequentially the number of layers) depends on the
 207 thickness of the sea ice sheet⁶ and the rates of change of the
 208 temperature and salinity profiles with the depth. Each layer in
 209 the SSCL model is characterized by thickness $d(m)$, lengths
 210 of $L_x(m)$ and $L_y(m)$ in x and y axes, respectively, and two
 211 rough interfaces between layer and the adjacent ones. By
 212 considering a constant temperature and salinity inside each
 213 layer, the particle density and the optical characteristics i.e.,
 214 absorption coefficient $a(m)$, scattering coefficient $b(m)$, and
 215 effective refractive index $n_e(m)$ are also constant for each
 216 layer in the SSCL model.

217 As shown in Table 1, each layer in the SSCL model is
 218 composed of a mixture of particles, i.e., a hosting medium
 219 with additional impurities. For instance, ice layers are com-
 220 posed of the pure ice as a hosting medium with a mixture
 221 of particles (e.g., brine pockets, air bubble, solid salt, algae

⁶The thickness of the sheet depends on the climate and the location of the sea ice. For instance, Worby et al. [31] reported the mean and standard deviation of the ice and snow thickness in Arctic, e.g., 0.87 ± 0.91 and 0.16 ± 0.2 metres, respectively, with a correlation length in kilometre range.

TABLE 1: Summary of references used to quantify the surface roughness and optical parameters of the SSCL model.

Surface Scatter Model				
Medium	Interface Roughness	Fixed Particle Density with z ?	Thickness	Layers Numbers
Seawater and atmosphere	[32]–[35]	Yes ([21], [22], [30, Ch. 3])	Meters range [21], [30]	Single layer
Ice and snow		No ([21], [22])	Centimeter range [31], [36]	Multi layers [20]–[22]
Particle Scatter Model				
Mixture Particles $j = \{1, 2, \dots, J_m\}$	Absorption Coefficient $a(m)$	Scattering Coefficient $b(m)$	Asymmetry Parameter $g(m)$	Refractive Index $n(m)$
Seawater Layer ($m = 1$)				
Pure water	[37, Tab. 3]	[38, First term in Eq. (19)]	[39]	[40, Tab. 1]
Chlorophyll-a	[41, Second term in Eq. (16)]	[38, Second term in Eq. (19)]	[39]	[42]
Yellow substance	[43, Eq. (1)]	\approx Zero	Null	[42]
Equivalent Seawater	Eq. (5)	Eq. (6)	Eq. (8)	Eq. (9)
m_i Ice Layers ($m = [2, 3, \dots, m_i + 1]$)				
Pure ice	[44, Fig. 3]	\approx Zero	Null	[40, Tab. 1]
Brine pocket	\approx Zero	[26], [25], [26]	[45, Fig. 7 (b)]	[45, Fig. 7]
Air bubble	\approx Zero	[26], [25], [20]	[45, Fig. 7 (b)]	[45, Fig. 7 a]
Solid salt	\approx Zero	[26], [25], [46]	[45, Fig. 7 (b)]	[45, Fig. 7 a]
Algae	[26, Fig. 7]	\approx Zero	Null	Ref. [42]
Soot	[42, Fig. 13]	\approx Zero	Null	[47]
Equivalent ice	Eq. (5)	Eq. (6)	Eq. (8)	Eq. (9)
m_s Snow Layers ($m = [m_i + 2, \dots, m_i + m_s + 1]$)				
Air	\approx Zero	\approx Zero	Null	\approx 1
Snow grains	[44, Fig. 3]	Eqs. [26], [26]	[48, Fig. 4]	[40, Tab. 1]
Algal impurities	[26, Fig. 9]	\approx Zero	Null	[42]
Non-algal impurities	[26, Fig. 9]	\approx Zero	Null	[42]
Soot	[42, Fig. 13 (a)]	\approx Zero	Null	Ref. [47]
Equivalent snow	Eq. (5)	Eq. (6)	Eq. (8)	Eq. (9)
Atmosphere Layer ($m = m_i + m_s + 2$)				
Gases (i.e. free space)	\approx Zero	\approx Zero	Null	1
Snowflakes	[49, Eq. (7)]	[50, Eq. (13)]	[51, Eq. (7)]	[40, Tab. 1]
Rain drops	[49, Eq. (6)]	[52, Eq. (7)]	[53], [54]	[40, Tab. 1]
Fog droplets	[49, Eq. (4)]	[55, Eq. (9)]	[53], [54]	[30, Eq. (27.6)]
Equivalent atmosphere	Eq. (5)	Eq. (6)	Eq. (8)	Eq. (9)

the entrance of each layer. The surface roughness of the interface is presented with the random height in the z direction for each point (x, y) , which can be well described in the x and y directions using the two-dimensional Gaussian distribution as measured in [32], [33]. To generate a realization of the ice surface, a two dimensional Gaussian random variable is generated with independent components in x and y according to [59]

$$p_{z_m}(z) = \frac{\exp\left(-\left[\frac{z^2}{2\sigma_x(m)^2} + \frac{z^2}{2\sigma_y(m)^2}\right]\right)}{\sqrt{2\pi\sigma_x(m)^2\sigma_y(m)^2}} \quad (10)$$

where z is the height at (x, y) point, and $\sigma_x(m)$ and $\sigma_y(m)$ are the RMS values in x and y directions⁷, respectively. As measured in [32], [33], the correlation between heights over the surface is well approximated using the two-dimensional generalized power-law function. Thus, to represent the correlation in space of the surface, the Gaussian realization can be filtered by a generalized power-law function. This function is given with one dimension in [34] and can be generalized to

⁷The experimental measurements in the Arctic and Antarctic regions revealed that the roughness parameters, RMS and correlation length, are in the millimetre and the centimetre ranges, respectively [34], [35].

two dimensions $p_{\rho_m}(\rho_x, \rho_y)$ as

$$p_{\rho_m}(\rho_x, \rho_y) = \exp\left(-\left[\left(\frac{\rho_x}{l_x(m)}\right)^\xi + \left(\frac{\rho_y}{l_y(m)}\right)^\xi\right]\right), \quad (11)$$

where ρ_x and ρ_y are the distances between correlated points in x and y directions, respectively, $l_x(m)$ and $l_y(m)$ are the correlation lengths in x and y directions, respectively. The value of ξ depends on the geographical location of the sea ice sheet, and is equal to 1 and 2 in cases of exponential-correlated and Gaussian-correlated surfaces, respectively. Note that, the surface roughness includes parts of the ice suspended in seawater. Due to the low density of these parts, they typically float up toward the ice sheet and settle on its bottom surface [1].

For the reader convenience, a summary of the equations and parameter values needed to quantify surface and optical parameters of the SSCL layers are given in Table 1. The compositions of each layer in the SSCL model are given in the table with references and equations needed to calculate the optical characteristics of each material.

III. THE SDOC LINK MODEL

In this section, we obtain an expression for the CIR of links between the AUV-Tx and the AUV-Rxs considering the effects of scattering, attenuation, as well as AUV-Rxs

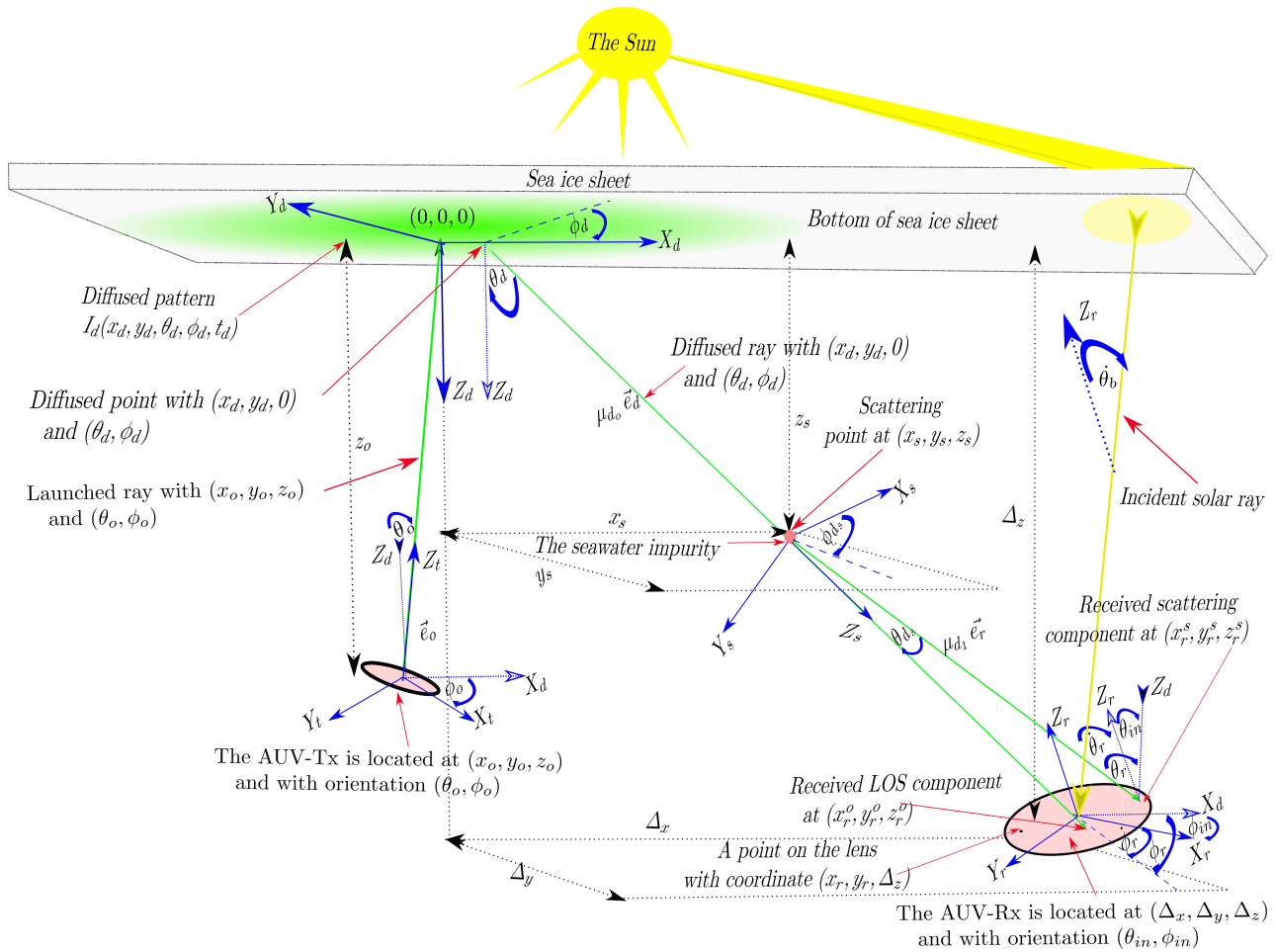


FIGURE 4: A model for the AUV-Tx to an AUV-Rx link (note that, the scattering in the seawater is only shown in the downward transmission for the sake of illustration simplicity).

294 configuration, position and orientation. Here, we introduce
 295 a new methodology that consists of two steps to obtain the
 296 CIR. In the first step, due to dense scattering occurring in
 297 the interior of the sea ice sheet, the upward transmission
 298 is evaluated numerically using an MCNRT approach. The
 299 MCNRT method obtains the diffusing pattern (e.g., the green
 300 ellipse in Figs. 1 and 4) that feeds the AUV-Rxs. In the second
 301 step, the downward transmission from the bottom of the sea
 302 ice sheet to an AUV-Rx is modeled analytically under a single
 303 scattering assumption in the seawater layer. This two-step
 304 methodology reduces computational complexity where the
 305 upward transmission is evaluated once regardless the number
 306 of the AUV-Rxs. As well, the CIR equation is a function of
 307 the configuration, position and orientation of the AUV-Rxs.

308 Figure 4 shows a link model between AUV-Tx and an
 309 AUV-Rx. The distances and angles are measured relative
 310 to the diffusing axes, (X_d, Y_d, Z_d) , which is centred at
 311 the bottom of the sea ice sheet. Relative to these axes, we
 312 assume that the AUV-Tx is located at (x_o, y_o, z_o) position
 313 and with aperture orientation polar and azimuth angles
 314 (θ_o, ϕ_o) . While the AUV-Rx is located at $(\Delta_x, \Delta_y, \Delta_z)$ position with

315 aperture polar and azimuthal inclination angles (θ_{in}, ϕ_{in}) .
 316 Thus, the AUV-Rx position can be described using the
 317 position and orientation (PO) vector (5×1) as $\Delta_r :=$
 318 $[\Delta_x; \Delta_y; \Delta_z; \theta_{in}; \phi_{in}]$. The AUV-Rx is equipped with a lens
 319 with diameter D_r and field of view (FOV) of θ_{FOV} .

320 A. UPWARD TRANSMISSION MODEL

321 As shown in Fig. 4, the AUV-Tx launches an optical beam
 322 with profile I_o , power P_o , wavelength λ_o , and beam width
 323 W_o toward the sea ice. The center of the beam is presented
 324 by a ray \vec{e}_o with directions (θ_o, ϕ_o) and a photon packet
 325 weight w_o (equivalent to optical intensity). Angles (θ_o, ϕ_o)
 326 correspond to intended and non-intended orientation for the
 327 optical beam. An intended orientation when is the AUV-Tx
 328 directs the optical beam with a specific direction toward the
 329 ice sheet. A non-intended orientation occurs disturbances in
 330 the environment such as sea currents and waves. Without
 331 loss of generality, we assume the spot of the beam on the
 332 bottom of the sea ice is centered at the origin, i.e., $(0, 0, 0)$.
 333 Thus, the position (x, y) of the AUV-Tx is obtained as $x_o =$
 334 $z_o \sin(\theta_o) \cos(\phi_o)$ and $y_o = z_o \sin(\theta_o) \sin(\phi_o)$. The depth

and orientation of the AUV-Tx are noted in a PO vector (3×1) as $\Delta_{\mathbf{t}} = [z_o; \theta_o; \phi_o]$.

Given the challenge of using analytic approaches to obtain the diffusing pattern produced from the ice sheet in the upward transmission, an MCRT method is used instead. In MCNRT, many optical rays \vec{e}_o are launched from the AUV-Tx to ensure the reliability of the result. The launched rays are diffused due to the surface and particle scattering taken place between and in the layers of the SSCL channel, respectively. The seawater, sea ice, snow and atmosphere layers contribute in producing the diffusing pattern, however, the sea ice and snow layers are the dominant contributors. The surface and particle scattering are simulated using geometric equations and numerical random process with associated PDFs, respectively, as given in the following subsections.

1) Surface Scattering

Surface scattering occurs when the optical ray strikes the rough interface between the m^{th} layer with refractive index $n_e(m)$ and the $(m+1)^{th}$ layer with refractive index $n_e(m+1)$ in upward propagation. Since $n_e(m) \neq n_e(m+1)$, the optical ray \vec{e}_o incident on the interface with an angle $\theta_i(m)$ is split into a reflected ray \vec{e}_1 to the m^{th} layer with an angle $\theta_r(m)$, where $\theta_i(m) = \theta_r(m)$, and a transmitted (i.e., refracted) ray \vec{e}_2 to the $(m+1)^{th}$ layer with an angle $\theta_t(m+1)$. The angle of transmitted ray between the m^{th} and $(m+1)^{th}$ layers is given by [60]

$$\theta_t(m+1) = \arcsin\left(\frac{n_e(m)}{n_e(m+1)} \sin(\theta_i(m))\right), \quad (12)$$

where, $\theta_i(m)$, $\theta_t(m+1)$, and $\theta_r(m)$ are measured relative to the local normal of the incident point which has a random direction due the randomness of the surface roughness. The reflection coefficient is computed for non polarized-light⁸ using angles $\theta_i(m)$ and $\theta_t(m+1)$ as [60]

$$R_s(m) = 0.5 \left[\left(\frac{\sin(\theta_i(m) - \theta_t(m+1))}{\sin(\theta_i(m) + \theta_t(m+1))} \right)^2 + \left(\frac{\tan(\theta_t(m+1) - \theta_i(m))}{\tan(\theta_i(m) + \theta_t(m+1))} \right)^2 \right], \quad (13)$$

and the corresponding transmission coefficient is obtained as $T_s(m+1) = 1 - R_s(m)$. Accordingly, the reflected and transmitted rays, \vec{e}_1 and \vec{e}_2 , propagate in m^{th} and $(m+1)^{th}$ layers with packet weights $w_1(m) = w_o \times R_s$ and $w_1(m+1) = w_o \times T_s$, respectively.

2) Particle Scattering

After the optical ray \vec{e}_1 enters the m^{th} layer, it will propagate a random distance $\mu_{u_o}(m)$ with a likelihood of particle scattering $p_{\mu}(\mu_{u_o}, m)$ given as [61]

⁸Modelling using non-polarized light is typical case of scattered light.

$$p_{\mu}(\mu_{u_o}, m) = c(m) \exp[-c(m) \mu_{u_o}(m)]. \quad (14)$$

and the random distance is generated as [61]

$$\mu_{u_o}(m) = -\frac{\log(1 - u_{\mu})}{c(m)}, \quad (15)$$

where u_{μ} is a uniform random variable, $u_{\mu} \sim U[0, 1]$, and $c(m)$ is the extinction coefficient of the m^{th} layer representing the loss in the power of the ray. The value of the extinction coefficient $c(m)$ is computed as

$$c(m) = a(m) + b(m). \quad (16)$$

When a scattering event occurs, the weight of the photon packet is dropped to [61]

$$w_3(m) = w_1(m) \frac{b(m)}{c(m)}. \quad (17)$$

Upon scattering, the optical ray arriving from the direction \vec{e}_1 will have a new direction \vec{e}_3 determined randomly according to polar and azimuthal scattering angles $(\theta_{u_s}, \phi_{u_s})$. The angle $\theta_{u_s}(m)$ is generated from the OTHG PDF in Eq. (7) as [61]

$$u_{\theta} = \int_0^{\theta_{u_s}(m)} p_{\theta_s}(\theta_s, m) \sin(\theta_s) d\theta_s, \quad (18)$$

where $u_{\theta} \sim U[0, 1]$. Also, the azimuthal scattering angle ϕ_{u_s} is typically described by a uniform PDF, and it is generated as [57]

$$p_{\phi_s}(\phi_{u_s}) = \frac{1}{2\pi}, \quad \phi_{u_s} = 2\pi u_{\phi} \quad (19)$$

where $u_{\phi} \sim U[0, 1]$. After scattering, the ray travels a new distance μ_{u_1} with a new direction \vec{e}_3 before the next scattering occurs with likelihood $p_{\mu}(\mu_{u_1}, m)$. Compared to the seawater and the atmosphere, particle scattering takes place much more frequently in snow and sea ice layers. Typically, the optical ray is scattered few times in the seawater or atmosphere layer, however, hundreds of scattering events can typically take place in the sea ice or snow layers.

The MCNRT traces the optical rays until they are either absorbed, trapped in the ice layer, escape to the atmosphere, or diffuse back into the seawater. The diffused rays only contribute in the obtained diffusing pattern for the upward transmission and the remainder of the rays are considered as lost. For a given position and orientation for the AUV-Tx, $\Delta_{\mathbf{t}}$, the normalized diffusing pattern is obtained with the intensity I_d as a function of the space, angles and time as follows

$$I_d(x_d, y_d, \theta_d, \phi_d, t_d | \Delta_{\mathbf{t}}) = \text{MCNRT}\{\text{SSCL}, \Delta_{\mathbf{t}}, I_o, \lambda_o, W_o\} \quad (20)$$

where, as shown in Fig. 4, the intensity I_d is measured on the bottom of the sea ice surface at position x_d and y_d , with polar

413 θ_d , azimuth ϕ_d angles, and time t_d . As well, the DC gain of
414 the upward transmission G_u is computed using I_d as

$$G_u = \int_{-L_x/2}^{L_x/2} \int_{-L_y/2}^{L_y/2} \int_0^{\pi/2} \int_0^{2\pi} \int_0^{\infty} I_d(x_d, y_d, \theta_d, \phi_d, t_d) dt_d d\phi_d d\theta_d dy_d dx_d, \quad (21)$$

415 where $L_x = \max\{L_x(m=2), \dots, L_x(m_i + m_s + 1)\}$ and
416 $L_y = \max\{L_y(m=2), \dots, L_y(m_i + m_s + 1)\}$ are the
417 considered lengths of the SSCL channel in x and y axes,
418 respectively.

419 B. DOWNWARD TRANSMISSION MODEL

420 Figure 4 shows a model for the downward transmission
421 which corresponds to the link from the bottom of the sea ice
422 to the AUV-Rx through the seawater channel. A diffused ray
423 emitted from a position $(x_d, y_d, 0)$ in the direction of \vec{e}_d
424 is represented in the figure, where \vec{e}_d is defined as

$$\vec{e}_d = \vec{x}_d \sin(\theta_d) \cos(\phi_d) + \vec{y}_d \sin(\theta_d) \sin(\phi_d) + \vec{z}_d \cos(\theta_d), \quad (22)$$

425 where $(\vec{x}_d, \vec{y}_d, \vec{z}_d)$ are the unit vectors in the direction of
426 (X_d, Y_d, Z_d) axes. The impurities in the seawater cause ab-
427 sorption and scattering for the diffused ray \vec{e}_d . Under a single
428 scattering assumption, which is reasonable here because the
429 link is short, \vec{e}_d arrives to the AUV-Rx either with LOS (i.e.,
430 non-scattering) or after one scattering with the direction \vec{e}_r .
431 In the LOS path, the direction is maintained (i.e. $\vec{e}_d = \vec{e}_r$)
432 and the ray arrives with arrival position (x_r^o, y_r^o, z_r^o) .

433 In the scattering path, let (x_s, y_s, z_s) denote the position
434 of the scattering event relative to (X_d, Y_d, Z_d) axes, and
435 with polar and azimuthal scattering angles $(\theta_{d_s}, \phi_{d_s})$ relative
436 to the axes of the scattering (X_s, Y_s, Z_s) , as shown in
437 Fig. 4. The scattering angles θ_{d_s} and ϕ_{d_s} are computed
438 using Eqs. (18) and (19) by replacing angles θ_{u_s} and
439 ϕ_{u_s} with angles θ_{d_s} and ϕ_{d_s} , respectively. The scattered
440 ray arrives to the receiver with polar and azimuthal ar-
441 rival angles (θ_r, ϕ_r) measured relative to the sea ice axes,
442 (X_d, Y_d, Z_d) . For given scattering angles $(\theta_{d_s}, \phi_{d_s})$, the
443 arrival angles (θ_r, ϕ_r) are computed from $(\theta_{d_s}, \phi_{d_s})$ as fol-
444 lows. Let \mathbf{e}_d be (3×1) vector, represented in (X_d, Y_d, Z_d)
445 as $\mathbf{e}_d = [\sin(\theta_d) \cos(\phi_d); \sin(\theta_d) \sin(\phi_d); \cos(\theta_d)]$. Then,
446 \mathbf{e}_d is rotated around (Y_s, X_s, Z_s) axes by two angles:
447 $\theta_y = \arcsin(\cos(\phi_{d_s}) \sin(\theta_{d_s}))$ and $\theta_x =$
448 $\arcsin(\sin(\phi_{d_s}) \sin(\theta_{d_s}) / \cos(\theta_y))$ respectively. Thus, θ_r
449 and ϕ_r are computed as

$$\begin{aligned} \theta_r &= \arccos([0, 0, 1] \mathbf{R}_x(\theta_x) \mathbf{R}_y(\theta_y) \mathbf{e}_d), \\ \phi_r &= \arcsin\left(\frac{[0, 1, 0] \mathbf{R}_x(\theta_x) \mathbf{R}_y(\theta_y) \mathbf{e}_d}{\sin(\theta_d)}\right), \end{aligned} \quad (23)$$

450 where $\mathbf{R}_x(\theta_x)$ and $\mathbf{R}_y(\theta_y)$ are (3×3) rotation matrices
451 around X_d and Y_d axes, respectively [62]. The arrival vector
452 \vec{e}_r is expressed with respect to the axes of the sea ice as

$$\vec{e}_r = \vec{x}_d \sin(\theta_r) \cos(\phi_r) + \vec{y}_d \sin(\theta_r) \sin(\phi_r) + \vec{z}_d \cos(\theta_r). \quad (24)$$

453 Vector \vec{e}_r is also characterized by arrival angles (θ_r, ϕ_r)
454 measured relative to the axes, (X_r, Y_r, Z_r) , as shown in the
455 Fig. 4, and can be equivalently written as

$$\vec{e}_r = \vec{x}_r \sin(\theta_r) \cos(\phi_r) + \vec{y}_r \sin(\theta_r) \sin(\phi_r) + \vec{z}_r \cos(\theta_r), \quad (25)$$

456 where $(\vec{x}_r, \vec{y}_r, \vec{z}_r)$ are the unit vectors relative to the Rx
457 axes (X_r, Y_r, Z_r) . For the given angles (θ_r, ϕ_r) , the an-
458 gles (θ_r, ϕ_r) are calculated from Eq. (23) by replacing
459 \mathbf{e}_d with $\mathbf{e}_r = [\sin(\theta_r) \cos(\phi_r); \sin(\theta_r) \sin(\phi_r); \cos(\theta_r)]$ and
460 substituting $\theta_y = \arcsin(\cos(\phi_{in}) \sin(\theta_{in}))$ and $\theta_x =$
461 $\arcsin(\sin(\phi_{in}) \sin(\theta_{in}) / \cos(\theta_y))$. The scattered ray ar-
462 rives at arrival position (x_r^s, y_r^s, z_r^s) over the aperture of the
463 AUV-Rx.

464 The arriving ray from the LOS or scattering path is de-
465 tected if the position of arrival (x_r, y_r, z_r) is located on the
466 lens of the AUV-Rx with arrival angles (θ_r, ϕ_r) less than half
467 angle of the FOV. This can be compactly represented as the
468 geometric loss G_g and it is written as

$$G_g(\Delta_r) = \begin{cases} 1, & \text{if } (x_r, y_r, z_r) \in f_p(D_r, \Delta_r) \text{ and } \theta_r \leq \frac{\theta_{FOV}}{2} \\ 0, & \text{otherwise,} \end{cases} \quad (26)$$

469 where $f_p(D_r, \Delta_r)$ represents the spatial extent of the AUV-
470 Rx lens with respect to the sea ice axes (X_d, Y_d, Z_d) .

471 1) Case 1: Low Scattering Seawater

472 Consider the case of seawaters with small scattering coef-
473 ficient (e.g., pure seawater) where the impact of scattering
474 is negligible. In this case, only the LOS component need to
475 be considered [63], [64]. In the LOS path, the direction is
476 maintained (i.e. $\vec{e}_d = \vec{e}_r$), and the amplitude of the optical ray
477 is attenuated according to the Beer-Lambert law. The LOS
478 ray arrives with arrival position (x_r^o, y_r^o, z_r^o) , shown in Fig. 4,
479 and is computed as [65]

$$\begin{aligned} x_r^o &= x_d + \Delta_z \tan(\theta_d) \cos(\phi_d), \\ y_r^o &= y_d + \Delta_z \tan(\theta_d) \sin(\phi_d), \\ z_r^o &= \Delta_z. \end{aligned} \quad (27)$$

481 For rays diffused from a single point on the bottom of the sea
482 ice $(x_d, y_d, 0)$, the CIR can be well approximated by a linear
483 combination of LOS components as

$$\begin{aligned} P^o(t_r, x_d, y_d) &\approx P_o \int_0^{\infty} \int_0^{2\pi} \int_0^{\pi/2} [\exp(-l_r^o c) G_g(\Delta_r) \\ &I_d(x_d, y_d, \theta_d, \phi_d, t_d) \delta\left(t_r - \left(t_d + \frac{l_r^o}{\nu}\right)\right)] d\theta_d d\phi_d dt_d \end{aligned} \quad (28)$$

484 where the length of the LOS path is computed geometrically
485 from the figure as $l_r^o = \sqrt{(x_d - x_r^o)^2 + (y_d - y_r^o)^2 + (z_d - z_r^o)^2}$.
486 The symbols t_r and ν are the arrival time and the light
487 speed in the seawater, respectively, and $\delta(\cdot)$ is the Dirac-delta
488 function.

2) Case 2: High Scattering Seawater

For the case of seawaters with relatively high scattering coefficient (e.g., clear and coastal seawaters), single scattering is significant relative to the LOS [63], [64]. Thus, both of the LOS and single scattering components are taken into account. Figure 4 shows the diffused ray traveling in the direction \vec{e}_d for a distance μ_{d_0} then is scattered in the direction \vec{e}_r and travel a distance μ_{d_1} before arriving the lens. The scattering position (x_s, y_s, z_s) and angle θ_{d_s} are given by [66]

$$\begin{aligned} x_s &= x_d + \mu_{d_0} \sin(\theta_d) \cos(\phi_d), & z_s &= \mu_{d_0} \cos(\theta_d), \\ y_s &= y_d + \mu_{d_0} \sin(\theta_d) \sin(\phi_d), & \theta_{d_s} &= \arccos(\vec{e}_d \cdot \vec{e}_r). \end{aligned} \quad (29)$$

This scattering results in a reduction in the photon packet weight of the ray \vec{e}_r by a factor of b/c relative to the packet of the ray \vec{e}_d . After scattering and traveling a distance μ_{d_1} , the ray arrives to a position (x_r^s, y_r^s, z_r^s) which is obtained as [66]

$$\begin{aligned} x_r^s &= x_s + \mu_{d_1} \sin(\theta_r) \cos(\phi_r), \\ y_r^s &= y_s + \mu_{d_1} \sin(\theta_r) \sin(\phi_r), \\ z_r^s &= z_s + \mu_{d_1} \cos(\theta_r). \end{aligned} \quad (30)$$

Using Eqs. (22)-(30), the CIR of single scattering components is derived by using a similar approach as in [63]. For rays diffused from a single point on the bottom of the sea ice $(x_d, y_d, 0)$, the CIR of received signal after single scattering is given as

$$\begin{aligned} P^s(t_r, x_d, y_d) &= P_o \int_0^\infty \int_0^{2\pi} \int_0^{\pi/2} I_d(x_d, y_d, \theta_d, \phi_d, t_d) \\ &\left[\frac{b}{2\pi} \times \int_0^{2\pi} \int_0^{\pi/2} p_{\phi_s}(\phi_{d_s}) p_{\theta_s}(\arccos(\vec{e}_d \cdot \vec{e}_r)) \times \right. \\ &\sin(\arccos(\vec{e}_d \cdot \vec{e}_r)) \int_0^{l_r^s} \exp(-cl_r^s) G_g(\Delta_{\mathbf{r}}) \times \\ &\left. \delta\left(t_r - \left(t_d + \frac{l_r^s}{\nu}\right)\right) d\mu_0 d\theta_r d\phi_{d_s} \right] d\theta_d d\phi_d dt_d, \end{aligned} \quad (31)$$

where the length of the single scattering path is computed as $l_r^s = \mu_{d_0} + \mu_{d_1}$, and μ_{d_1} is computed using Eqs. (30) and (29) as

$$\mu_{d_1} = \frac{\Delta z - \mu_{d_0} \cos(\theta_d)}{\cos(\theta_r)}. \quad (32)$$

The overall CIR is the summation of the LOS and scattering components, and it is computed using Eqs. (28) and (31) as

$$P(t_r, x_d, y_d) = P^o(t_r, x_d, y_d) + P^s(t_r, x_d, y_d). \quad (33)$$

The CIR for the link between the AUV-Tx and an AUV-Rx with PO vector $\Delta_{\mathbf{r}}$ is computed by integration over all the points on the bottom of the sea ice (x_d, y_d) as

$$\begin{aligned} P(t_r | \Delta_{\mathbf{r}}) &= \int_{-L_y/2}^{L_y/2} \int_{-L_x/2}^{L_x/2} [P^o(t_r, x_d, y_d | \Delta_{\mathbf{r}}) + \\ &P^s(t_r, x_d, y_d | \Delta_{\mathbf{r}})] dx_d dy_d, \end{aligned} \quad (34)$$

Equation (34) can be used to determine the link budget and the induced pulse dispersion. The DC gain of a downward transmission (i.e., AUV-Tx to an AUV-Rx link) is obtained from CIR as [67]

$$h_o(\Delta_{\mathbf{r}}) = \frac{1}{P_o} \left(\int_0^\infty P(t_r | \Delta_{\mathbf{r}}) dt_r \right), \quad (35)$$

where P_o is the transmitted power as defined in the link model. As well, RMS of the pulse spreading is computed as [67]

$$\tau_{RMS}(\Delta_{\mathbf{r}}) = \sqrt{\frac{\int_0^\infty (t_r - \tau_o)^2 P(t_r | \Delta_{\mathbf{r}})^2 dt_r}{\int_0^\infty P(t_r | \Delta_{\mathbf{r}})^2 dt_r}}, \quad (36)$$

where, τ_o is the mean excess delay given by [67]

$$\tau_o(\Delta_{\mathbf{r}}) = \frac{\int_0^\infty t_r P(t_r | \Delta_{\mathbf{r}})^2 dt_r}{\int_0^\infty P(t_r | \Delta_{\mathbf{r}})^2 dt_r}. \quad (37)$$

The system of Equations, (22)-(37), are used to quantify the link performance between the AUV-Tx and the AUV-Rxs as shown in Section V.

IV. A SYSTEM DESIGN FOR SDOC APPROACH

Though the proposed SDOC approach provides a broadcast communication link without requirement for alignment, its performance is limited by the high channel attenuation and inter-symbol interference (ISI) due to multipath propagation. The ISI is induced mainly by the sea ice sheet in the upward transmission, but also, in the downward transmission due to the scattering occurring in the seawater. In addition, the performance can be degraded by background radiations due to the fact that the AUVs navigate near the bottom of the sea ice and the orientation of the receivers are aligned upwards, as shown in Fig. 4. In this section, inspired by indoor OWC systems [12]–[16], we propose appropriate Tx and Rx architectures to tackle these limitations. This communication architecture can be considered as a first prototype step in the development of such links. We also discuss practical implementation considerations of SDOC links.

A. SYSTEM MODEL

Figure 5 shows the overall block diagram of the proposed SDOC system, as described in the following.

1) Transmitter

The proposed architecture is shown in Fig. 5a. For simplicity, the transmitted data are encoded using intensity modulation direct detection (IM/DD) with non-return-to-zero OOK (NRZ-OOK) modulation scheme [68]. As well, for simplicity, we consider the LD to be switched fully on and off corresponding to ones and zeros of the OOK symbols, respectively, i.e., zero extinction ratio. The OOK symbol duration is T_b , the transmitted data rate is $R_b = 1/T_b$, the electrical bandwidth $B \approx R_b$, the average transmitted optical power is $P_o = p_p/2$, where p_p denotes the transmitted optical

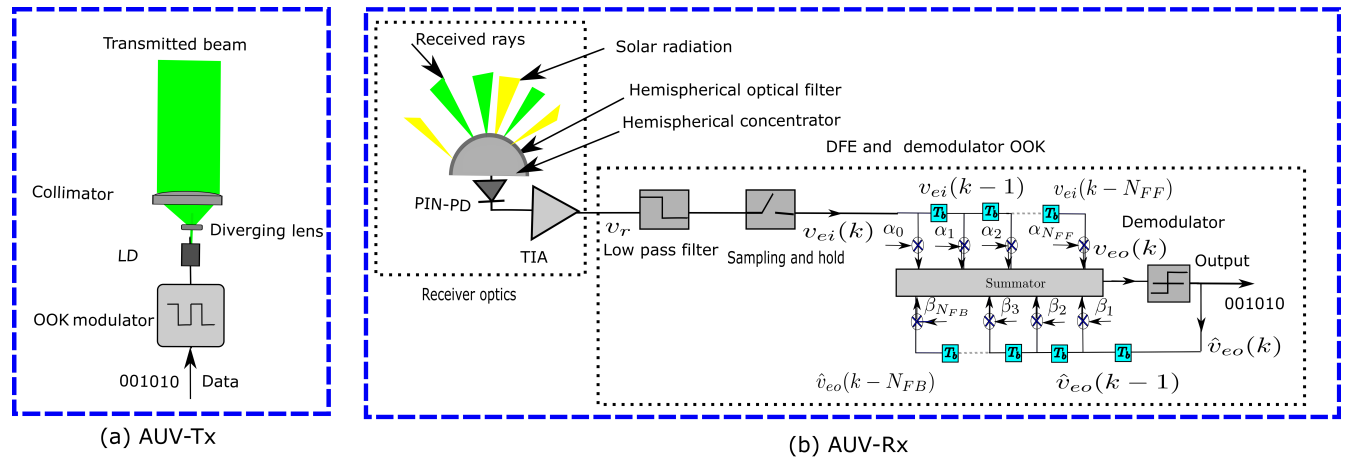


FIGURE 5: The proposed system architecture for the SDOC approach.

power during the on slots. Consider a LD with green wavelength ($\lambda_o = 532$ nm) given its relatively low attenuation in seawater [69]. A beam expander is the LD implemented using two lenses, one lens for beam diverging and other one for beam collimating. This collimated wide beamwidth optical beam helps in transmitting more optical power while keeping the constraint of the maximum permissible exposure (MPE) optical power on the eye⁹ regarding eye safety.

2) Receiver Optoelectronics

The proposed Rx architecture is shown in Fig. 5b. First, the AUV-Rx uses a hemispheric concentrator which is implemented using a hemispherical non-imaging lens coated by a bandpass optical filter as shown. Such a lens with a relatively large diameter, D_r , and a wide FOV, θ_{FOV} , is desired to collect much of diffused rays to compensate SDOC high channel attenuation. As well, an optical filter with narrow bandwidth, $\Delta\lambda$, is preferred to eliminate the incoming background radiation from the sun during the daytime. The concentrator is an essential component in the SDOC approach especially with high background radiation levels at $\lambda_o = 532$ nm [72]. The concentrator is quantified by its gain G_c which depends on its refractive index, n_c , and the FOV as [73]

$$G_c(\dot{\theta}_b) = \begin{cases} \frac{n_c^2}{\sin(\theta_{FOV}/2)^2} & \text{if } \dot{\theta}_b \leq \theta_{FOV}/2, \\ 0 & \text{if } \dot{\theta}_b > \theta_{FOV}/2, \end{cases} \quad (38)$$

where $\dot{\theta}_b$ is the incident angle of the background ray upon the concentrator and it is measured relative to the optical axis of the Rx, Z_r , as shown in Fig. 4. As well, the optical band pass filter is quantified by its transmission coefficient $T(\dot{\theta}_b)$ which

depends on the incident angle of the received ray. Such hemispheric concentrators are commercially available and have been used in optical diffusing communication systems for indoor applications¹⁰. The concentrator enlarges the effective area of the PD, A_{ef} , which means capturing solar noise. The effective area of the PD is obtained as [73]

$$A_{ef}(\dot{\theta}_b) = \begin{cases} A_{PD} T(\dot{\theta}_b) G_c(\dot{\theta}_b) \cos(\dot{\theta}_b) & \text{if } \dot{\theta}_b \leq \theta_{FOV}/2 \\ 0 & \text{if } \dot{\theta}_b > \theta_{FOV}/2 \end{cases} \quad (39)$$

where A_{PD} denotes the physical active area of the PD. Here, for simplicity, the dependence of the effective area on the incident angle $\dot{\theta}_b$ is represented by replacing $A_{ef}(\dot{\theta}_b)$ by its average $\overline{A_{ef}}$ over the incident angle, while making two assumptions. Firstly, we assume that the function $T(\dot{\theta}_b)$ can be replaced by its average, \overline{T} , over all incident angles. This assumption holds, especially, when the incident optical ray arrives within a wide range of the angles which is the typical case of diffusing communications [73]. Secondly, we assume a uniform PDF for $\dot{\theta}_b$. Then, the average Rx effective area is obtained as

$$\overline{A_{ef}} = \frac{2}{\pi} \int_0^{\theta_{FOV}/2} A_{ef}(\dot{\theta}_b) d\dot{\theta}_b = \frac{2 A_{PD} \overline{T} n_c^2}{\pi \sin(\theta_{FOV}/2)}. \quad (40)$$

Note that, enlarging the FOV decreases the the average effective area of the Rx.

After the hemispherical concentrator, a silicon PIN photodiode (PIN-PD) with a trans-impedance amplifier (TIA) is used. The PIN-PD converts the collected optical rays to an electrical current proportionally to its responsivity \mathfrak{R} and A_{PD} . Then, the TIA converts the small current to a high voltage proportionally to its load resistance R_L . In contrast to avalanche photodiodes, photo-multiplier tube and SiPM PDs, the silicon PIN-PD achieves a better performance when the background radiation is much high and dominants the receiver noises [76], [77].

¹⁰The optical concentrator and filter with the mentioned specifications can be implemented [74]. However, some customization may be required for use in underwater applications [75].

3) Channel Equalization

Using the described setup, the Rx can overcome the effects of high channel attenuation and background noise. A low pass filter (LPF) is employed after the TIA to eliminate any out-of-band noise, where the filter bandwidth is adjusted according to the actual data rate. The bandwidth of the filter is adopted according to the link speed to maximize the system performance. The output signal of the LPF is sampled with sampling rate T_s , where $T_s < T_b/2$ to avoid aliasing [78]. The sampled signal is then processed by a discrete-time channel equalizer to reduce the impact of ISI. Among the available equalization schemes, the digital decision feedback equalizer (DFE) is chosen due to the mobility of the AUVs [79]. With proper training, the DFE can adapt itself to the changing channel conditions and the PO vector. As well, the DFE coupled with the least mean squares (LMS) algorithm has the advantage of simplicity and is a good choice for non-fading dispersive channels [79]. As shown in Fig. 5b, the DFE has two input branches namely, feed forward (FF) and feedback (FB). The input through the FF is the electrical signal from the output of the sampler $v_{ei}(k)$, where k indicates to the index of the received sample. While, the input through the FB is the output of the OOK demodulator $\hat{v}_{eo}(k)$, where $\hat{v}_{eo}(k) \in \{1, 0\}$. The output of the equalizer is the summation of the weighted inputs as follows [79]

$$v_{eo}(kT_b) = \sum_{j_F=0}^{N_{FF}} \alpha_{j_F} v_{ei}(kT_b - j_F T_b) + \sum_{j_B=1}^{N_{FB}} \beta_{j_B} \hat{v}_{eo}(kT_b - j_B T_b), \quad (41)$$

where α_{j_F} and β_{j_B} are the FF and FB weighting coefficients, respectively. Symbols N_{FF} and N_{FB} indicates the number of the tabs used in the FF and FB filters, respectively. The DFE has two operation modes, training and tracking modes. In the training mode, the Tx sends a training sequence which is known to the Rx. The DFE adopts the LMS algorithm to obtain the optimal values for α_{j_F} and β_{j_B} [79]. In the tracking mode, the DFE uses the optimal values obtained for the gains vector to eliminate the effect of ISI in the transmitted OOK symbols. In the next subsection, we discuss the effect of non-ideal performance of the DFE and the different noise sources on the SINR of the SDOC system.

B. SIGNAL-TO-INTERFERENCE-PLUS-NOISE RATIO ANALYSIS

During training, the filter coefficients are adapted based on output of OOK decision device and the training sequence [78]. In the tracking mode, assuming that training was successful, error propagation at the output of the decision device should be minimized. Assuming an absence of decision errors, a simple linear model of the the DFE output voltage can

be approximated as

$$v_{eo}(kT_s, \Delta_{\mathbf{r}}) \approx \underbrace{v_n(kT_s, \Delta_{\mathbf{r}})}_{\text{noise}} + \underbrace{P_{DFE}(kT_s) \otimes (R_L \Re [p(\tau) * P(\tau, \Delta_{\mathbf{r}})] |_{\tau_s=kT_s})}_{\text{signal + residual ISI}} \quad (42)$$

where, v_n is the sampled noise voltage, and $\Delta_{\mathbf{r}}$ is PO vector of the AUV-Rx as defined in the previous section, $P_{DFE}(kT_s)$ is the sampled system impulse response of the DFE, \otimes is the discrete convolution operator, $*$ is continuous convolution and $p(t)$ is the instantaneous transmitted optical power. The signal in Eq. (42) can be decomposed as the sum of the desired signal, denoted by $v_s(\Delta_{\mathbf{r}})$, and the residual ISI denoted by $v_{isi}(\Delta_{\mathbf{r}})$ where,

$$v_s(\Delta_{\mathbf{r}}) \approx v_n(kT_s, \Delta_{\mathbf{r}}) + \sum_{k=\tau_d/T_s}^{(T_b+\tau_d)/T_s} P_{DFE}(kT_s) \otimes (R_L \Re [p(\tau) * P(\tau, \Delta_{\mathbf{r}})] |_{\tau_s=kT_s}), \quad (43)$$

where τ_d is the time delay of the channel and T_b and τ_d are assumed to be multiples of T_s . Also,

$$v_{isi}(\Delta_{\mathbf{r}}) \approx v_n(kT_s, \Delta_{\mathbf{r}}) + \sum_{k=(T_b+\tau_d)/T_s}^{\infty} P_{DFE}(kT_s) \otimes (R_L \Re [p(\tau) * P(\tau, \Delta_{\mathbf{r}})] |_{\tau_s=kT_s}). \quad (44)$$

The noise contribution in (42) includes the effects of the thermal v_{th} and shot v_{sh} noises, i.e., $v_n = v_{th} + v_{sh}$. The thermal noise v_{th} is well described by zero mean Gaussian distribution with variance σ_{th}^2 given as [80], [81]

$$\sigma_{th}^2 = 4 R_L K [T(m=1) + 273.15] B, \quad (45)$$

where, K is the Boltzmann constant and $T(m=1)$ is the temperature of the seawater layer in Celsius as defined in Sec. II-B. Usually, the temperature of the seawater underneath sea ice is $T(m=1) \leq 0$ °C, as shown in Fig. 2. On the other hand, the shot noise is associated with the superposition of the desired signal voltage v_s , the ISI distortion voltage v_{isi} , and the background radiation voltage v_{sun} . Due to the high intensity of the solar radiation, the shot noise can be modeled using Gaussian random process with variance given as [80]

$$\sigma_{sh}^2(\Delta_{\mathbf{r}}; \Lambda) = 2 R_L q [\Lambda v_s(\Delta_{\mathbf{r}}) + v_{isi}(\Delta_{\mathbf{r}}) + v_{sun}(\Delta_{\mathbf{r}})] B, \quad (46)$$

where q is the electron charge in electron-volt units and $\Lambda = 1$ and $\Lambda = 0$ with on and off of the OOK symbols, respectively. The value of v_{sun} is quantified as [76]

$$v_{sun}(\Delta_{\mathbf{r}}) = \begin{cases} \frac{R_L \Re (1 - G_u) \Delta \lambda E_s \overline{A_{ef}} \cos(\theta_{inc})}{\exp(K_d \Delta z)} \\ 0 & \text{if } \theta_{inc} > \theta_{FOV}/2 \end{cases} \quad (47)$$

where, the E_s is the spectral solar intensity with unit Watt/(m². nm), and K_d is the light diffusion coefficient

688 in the seawater. The value of E_s depends on the weather
689 conditions, as well the zenith angle of the sun [72]. The
690 zenith angle is in range 25° to 90° in Arctic and Antarctic
691 regions where frozen oceans exist, and it records a minimum
692 value during the summer seasons [82]. The light diffusing
693 coefficient is related to the seawater parameters by $K_d =$
694 $a(m = 1) + 0.03b(m = 1)$. The factor of $(1 - G_u)$
695 represents the transmission coefficient of the sea ice sheet.
696 This means a thicker sea ice sheet assists in raising the gain
697 of the upward transmission and in reducing the received
698 background radiations.

699 The mean η_Λ and the variance σ_Λ^2 , $\Lambda \in \{0, 1\}$, of the total
700 signal and noise affects system performance are given as

$$\begin{cases} \eta_\Lambda(\Delta_{\mathbf{r}}; \Lambda) = \Lambda v_s(\Delta_{\mathbf{r}}) + v_{isi}(\Delta_{\mathbf{r}}) + v_{sun}(\Delta_{\mathbf{r}}) \\ \sigma_\Lambda^2(\Delta_{\mathbf{r}}; \Lambda) = \sigma_{isi}^2(\Delta_{\mathbf{r}}) + \sigma_{sh}^2(\Delta_{\mathbf{r}}; \Lambda) + \sigma_{th}^2 \end{cases} \quad (48)$$

701 where σ_{isi}^2 is the variance of ISI signals and it is equal to
702 $R_L v_{isi}^2/4$. Thus, the instantaneous SINR, $\gamma(\Delta_{\mathbf{r}})$, is obtained
703 as

$$\gamma(\Delta_{\mathbf{r}}) = \frac{[\eta_1(\Delta_{\mathbf{r}}) - \eta_0(\Delta_{\mathbf{r}})]^2}{[\sigma_1(\Delta_{\mathbf{r}}) + \sigma_0(\Delta_{\mathbf{r}})]^2} = \frac{v_s^2(\Delta_{\mathbf{r}})}{[\sigma_1(\Delta_{\mathbf{r}}) + \sigma_0(\Delta_{\mathbf{r}})]^2}. \quad (49)$$

704 In the numerical results, we consider three configurations
705 for the AUV-Rxs, namely, unequalized AUV-Rx (Rx-UE),
706 AUV-Rx with DFE (Rx-E), and AUV-Rx with perfect DFE
707 (Rx-PE). The BER of the Rx-E and Rx-UE systems are eval-
708 uated numerically using Monte Carlo simulations. However,
709 the BER of the Rx-PE system is evaluated by eliminating the
710 effect of ISI from (49), i.e. $v_{isi} = 0$, then using the well
711 known AWGN channel as [83]

$$p_e(\Delta_{\mathbf{r}}) = Q\left(\sqrt{\gamma(\Delta_{\mathbf{r}})}\right) \quad (50)$$

712 where $Q(x) = 1/\sqrt{2\pi} \int_x^\infty \exp(-[z/\sqrt{2}]^2) dz$.

713 V. NUMERICAL RESULTS AND DISCUSSIONS

714 In this section, we numerically evaluate the diffusing patterns
715 of upward transmission, the CIRs of downward transmission,
716 and overall system performance. We assume that the AUV-Tx
717 is located at depth $z_o = 2$ m, and perfectly orientated to the
718 bottom of the sea ice, i.e., $\theta_0 = \phi_0 = 0$ and $(x_o, y_o) = (0, 0)$.
719 The AUV-Tx is equipped with a laser source which emits
720 a collimated beam I_o with uniform intensity, wavelength
721 $\lambda_o = 532$ nm, average transmitted power $P_o \leq 200$ mW, and
722 a width of $W_o = 5$ cm to maintain eye-safety. However, we
723 assume the AUV-Rx moves in the x - y plane where the length
724 of the downward transmission does not exceed the limit of the
725 single scattering assumption. Note that the single scattering
726 assumption is valid with lengths 13.5 and 6.6 m for clear and
727 coastal seawaters, respectively [65]. Note that in the follow-
728 ing results, the particular values for parameters of the AUV-
729 Rx were not optimized for communication performance but
730 were chosen to demonstrate the range of operating conditions
731 of the SSCL channel.

732 We consider four SSCL channels, namely, a clear and
733 coastal seawater with a snow-covered sea ice sheet (CI-S and

734 Co-S channels) and the clear and coastal seawater with a bare
735 sea ice sheet (CI-B and Co-B channels). The snow-covered
736 sea ice sheet has a thickness of 36 cm and it well described by
737 Eqs. (1), (2). The bare sea ice sheet has thickness 12 cm and
738 its temperature and salinity profiles are described by Eqs. (3),
739 (4). We use Eqs. (1)-(9) and Table 1 to calculate the optical
740 and roughness parameters associated with each SSCL layer,
741 where the results are given in Table 2.

742 The bare-ice cases are divided into 6 layers while the
743 snow-covered cases are divided into 9 layers¹¹. In all cases,
744 each layer is assigned with the average values of the salinity
745 and temperature using Eqs. (1)-(4), as shown in Tables 2a
746 and 2b. Clear weather above the sea ice sheets is assumed,
747 which is the typical case during sunny days. As shown in
748 Tables 2a and 2b, the scattering coefficients of the snow-
749 covered sea ice sheet and coastal seawater are higher than
750 that for bare sea ice sheet and clear seawater, respectively.
751 In addition, it is clear that the changes in the refractive
752 indices and asymmetry parameters are small. In Table 2c, the
753 RMS of the roughness and correlation length, are assumed in
754 millimetre and centimetre ranges, respectively, as measured
755 in [34], [35]. As well, we assume isotropic layers (i.e.,
756 $\sigma_x(m) = \sigma_y(m)$ and $l_x(m) = l_y(m)$), and the interfaces are
757 Gaussian-correlated (i.e., $\xi = 2$) [32], [33]. The interfaces
758 between the ice layers are assumed smooth due to fact that
759 the variation in the effective refractive indices are negligible
760 in the presented cases. To ensure an accurate realization for
761 the SSCL model, the roughness is sampled with intervals
762 and lengths with values $\delta_x(m) = \delta_y(m) = 0.1 l_x(m)$ and
763 $L_x(m) = L_y(m) = 60 l_x(m)$ [84].

764 A. RESULTS FOR UPWARD TRANSMISSION

765 Figure 6 shows the marginalized diffusing patterns¹² for the
766 CI-B and CI-S channels with the orange and maroon colors,
767 respectively. The diffusing pattern is measured at the bottom
768 of the sea ice, i.e., $\Delta_z = 0$, with DC gains of $G_u = 0.26$ and
769 0.37 for CI-B and CI-S channels, respectively. These results
770 were obtained by running the MCNRT using the ZeMax
771 Opticstudio software [85] over 10^6 iterations. Note that we
772 have verified that increasing the number of iterations to 10^7
773 resulted in almost identical results.

774 Figures 6a and 6b show the marginalized diffusing patterns
775 versus the polar and the azimuthal angles, $I_{d\downarrow\theta}$ and $I_{d\downarrow\phi}$,
776 respectively. As shown in these figures, the marginalized
777 intensity is uniform with respect to (w.r.t.) ϕ_d , however, it
778 is oriented w.r.t. θ_d with a peak at $\theta_d \approx 45^\circ$. The ori-
779 entation indicates non-specular diffusing due to the dense
780 scattering occurred in the sea ice and snow. The value of
781 45° is interrupted as follows; each diffusing point on the sea
782 ice is an identical random variable described by Eq. (18),
783 and the diffusing pattern is a summation of that diffusing
784 points. Assuming the central limit theory, $I_{d\downarrow\theta}$ approaches

¹¹This is done as a compromise between the accuracy and the computa-
tional complexity of the MCNRT method.

¹²The marginalized diffusing pattern with x_d variable, for instance, is
obtained by integrating Eq. (20) over all remaining variables.

TABLE 2: The parameters of seawater bare sea ice and seawater snow-covered sea ice cascaded models.

(a) The CI-B and Co-B SSCL channels.

Layer No. (m)	$a(m)$ [1/m]	$b(m)$ [1/m]	$g(m)$	$n_e(m)$
$m = 6$ (Clear Air, $T = -14\text{ }^\circ\text{C}$, $S \approx 0\text{ ppt}$)	0	0	0	1
$m = 5$ (Ice, $T = -13.56\text{ }^\circ\text{C}$, $S = 7.19\text{ ppt}$)	0.563	480.473	0.9894	1.3494 - 0.0395i
$m = 4$ (Ice, $T = -9.635\text{ }^\circ\text{C}$, $S = 5.91\text{ ppt}$)	0.492	422.4211	0.9906	1.3496 - 0.0395i
$m = 3$ (Ice, $T = -6.38\text{ }^\circ\text{C}$, $S = 5.53\text{ ppt}$)	0.483	473.9	0.9923	1.3499 - 0.0395i
$m = 2$ (Ice, $T = -2.6\text{ }^\circ\text{C}$, $S = 5.91\text{ ppt}$)	0.721	996.81	0.9946	1.3504 - 0.0395i
$m = 1$ (Clear Seawater, $T = 0\text{ }^\circ\text{C}$, $S = 5.91\text{ ppt}$)	0.069	0.08	0.8708	1.333
$m = 1$ (Coastal Seawater $T = 0\text{ }^\circ\text{C}$, $S = 5.91\text{ ppt}$)	0.088	0.216	0.9470	1.333

(b) The CI-S and Co-S SSCL channels.

Layer No. (m)	$a(m)$ [1/m]	$b(m)$ [1/m]	$g(m)$	$n_e(m)$
$m = 9$ (Clear Air, $T = -12\text{ }^\circ\text{C}$, $S \approx 0\text{ ppt}$)	0	0	0	1
$m = 8$ (Snow, $T = -11.5\text{ }^\circ\text{C}$, $S \approx 0\text{ ppt}$)	0.282	3.1593×10^3	0.8878	1.1620 - 0.0395i
$m = 7$ (Ice, $T = -10.06\text{ }^\circ\text{C}$, $S = 11.9\text{ ppt}$)	0.532	845.81	0.9900	1.3445 - 0.0395i
$m = 6$ (Ice, $T = -8.56\text{ }^\circ\text{C}$, $S = 8.99\text{ ppt}$)	0.4661	645.03	0.9903	1.3451 - 0.0395i
$m = 5$ (Ice, $T = -6.57\text{ }^\circ\text{C}$, $S = 7.77\text{ ppt}$)	0.463	652.64	0.9913	1.3453 - 0.0395i
$m = 4$ (Ice, $T = -4.65\text{ }^\circ\text{C}$, $S = 6.66\text{ ppt}$)	0.451	760.68	0.9926	1.3455 - 0.0395i
$m = 3$ (Ice, $T = -3.63\text{ }^\circ\text{C}$, $S = 7.961\text{ ppt}$)	0.4532	724.321	0.9930	1.3454 - 0.0395i
$m = 2$ (Ice, $T = -2.34\text{ }^\circ\text{C}$, $S = 7.97\text{ ppt}$)	0.684	1334.457	0.9943	1.3457 - 0.0395i
$m = 1$ (Clear Seawater, $T = 0\text{ }^\circ\text{C}$, $S = 7.97\text{ ppt}$)	0.069	0.08	0.8708	1.333
$m = 1$ (Coastal Seawater $T = 0\text{ }^\circ\text{C}$, $S = 7.97\text{ ppt}$)	0.088	0.216	0.9470	1.333

(c) The roughness parameters for the interfaces between the layers of the SSCL channel models [34], [35].

The Interface	$\sigma_{x_m} = \sigma_{y_m}$ [mm]	$l_{x_m} = l_{y_m}$ [mm]	The Interface	$\sigma_{x_m} = \sigma_{y_m}$ [mm]	$l_{x_m} = l_{y_m}$ [mm]
Snow-Air	1.2	50	Ice-Snow	2	75
Ice-Air	5	120	Seawater-Ice	2.2	100

785 the Gaussian with mean 45° which the mean of the range; 0-
 786 90 degrees. In addition, the marginalized intensity in case of
 787 CI-S channel is relatively higher than the case of CI-B chan-
 788 nel. Specifically, the peaks of the marginalized intensities in
 789 Fig. 6a are 6×10^{-4} and 4×10^{-4} for CI-S and CI-B channels,
 790 respectively. Furthermore, the marginalized intensities in Fig.
 791 6b are 3.5×10^{-4} and 2.5×10^{-4} for CI-S and CI-B channels,
 792 respectively. The pattern in these figures can be fit to two-
 793 dimensional Lambertian and uniform functions in θ_d and ϕ_d
 794 respectively, for both CI-B and CI-S channels ¹³

$$I_{d\downarrow\theta,\phi}^{\text{CI-S}}(\theta_d, \phi_d) = 4.438 \times 10^{-5} \cos^{6.6}(\theta_d - 0.248\pi), \quad (51a)$$

$$I_{d\downarrow\theta,\phi}^{\text{CI-B}}(\theta_d, \phi_d) = 6.032 \times 10^{-5} \cos^{6.5}(\theta_d - 0.242\pi). \quad (51b)$$

795 Figure 6c shows the marginalized intensities $I_{d\downarrow x}$ versus
 the distance $x_d = [-0.5, 0.5]$ m. The intensities decay
 exponentially with peaks 1×10^{-3} and 1.8×10^{-3} at the
 center, $x_d = 0$ m, for the CI-B and CI-S SSCL channels,
 respectively, and almost zero value at $|x_d| = 0.5$ m. Due to
 the uniform value of the marginalized intensities w.r.t. ϕ_d , the
 intensity profiles for x_d and y_d are similar and can be fitted

¹³In this paper, the fitting is accomplished using the tool of curve fitting in Matlab [86, CFTOOL]. The goodness of the fit R-square = {0.8574, 0.8714} and RMSE = { 5.95×10^{-6} , 7.606×10^{-6} } for CI-B and CI-S channels, respectively.

with the following two-dimensional functions for the CI-B and CI-S SSCL channels as¹⁴

$$I_{d\downarrow x,y}^{\text{CI-B}}(x_d, y_d) = \frac{0.591}{10^3} \exp(-10.95|x_d| - 11.3|y_d|), \quad (52a)$$

$$I_{d\downarrow x,y}^{\text{CI-S}}(x_d, y_d) = \frac{1.466}{10^3} \exp(-15.41|x_d| - 15.46|y_d|). \quad (52b)$$

796 Though, the diffusing pattern has a small spot on the bottom
 797 of the sea ice sheet (i.e., $|x_d|$ and $|y_d| \leq 0.5$ m), due to
 798 the orientation with angle 45° , the spot expands out with the
 799 propagation in the seawater as shown in the next subsection.

800 Figure 6d shows the marginalized diffusing pattern $I_{d\downarrow t}$
 (i.e., temporal dispersion patterns of the upward transmis-
 801 sion) with $t_d = [2, 24]$ ns. The pattern of the CI-S channel
 802 has a high peak with amplitude 14×10^{-3} and it decays
 803 slowly with a long dispersion time due to the thickness and
 804 much particle scattering occurred for the laser beam in the
 805 channel as can be seen from Table 2b (i.e., a larger thickness,
 806 and higher temperature and salinity values). In contrast to
 807 the CI-S channel, the pattern of the CI-B channel has two
 808 peaks with amplitudes 32×10^{-4} and 26×10^{-4} . The time
 809 interval between the two peaks is nearly equal to the time
 810 taken by the optical ray to propagate from the bottom to the
 811 surface of the ice sheet. Thus, the shown dispersion pattern
 812 can reveal information about the thickness of the bare sea
 813 ice sheets whilst performing a communication function. The
 814

¹⁴The corresponding goodness of the fit criteria are; R-square = {0.9053, 0.9261} and RMSE = { 1.522×10^{-5} , 2.505×10^{-5} } for CI-B and CI-S channels, respectively.

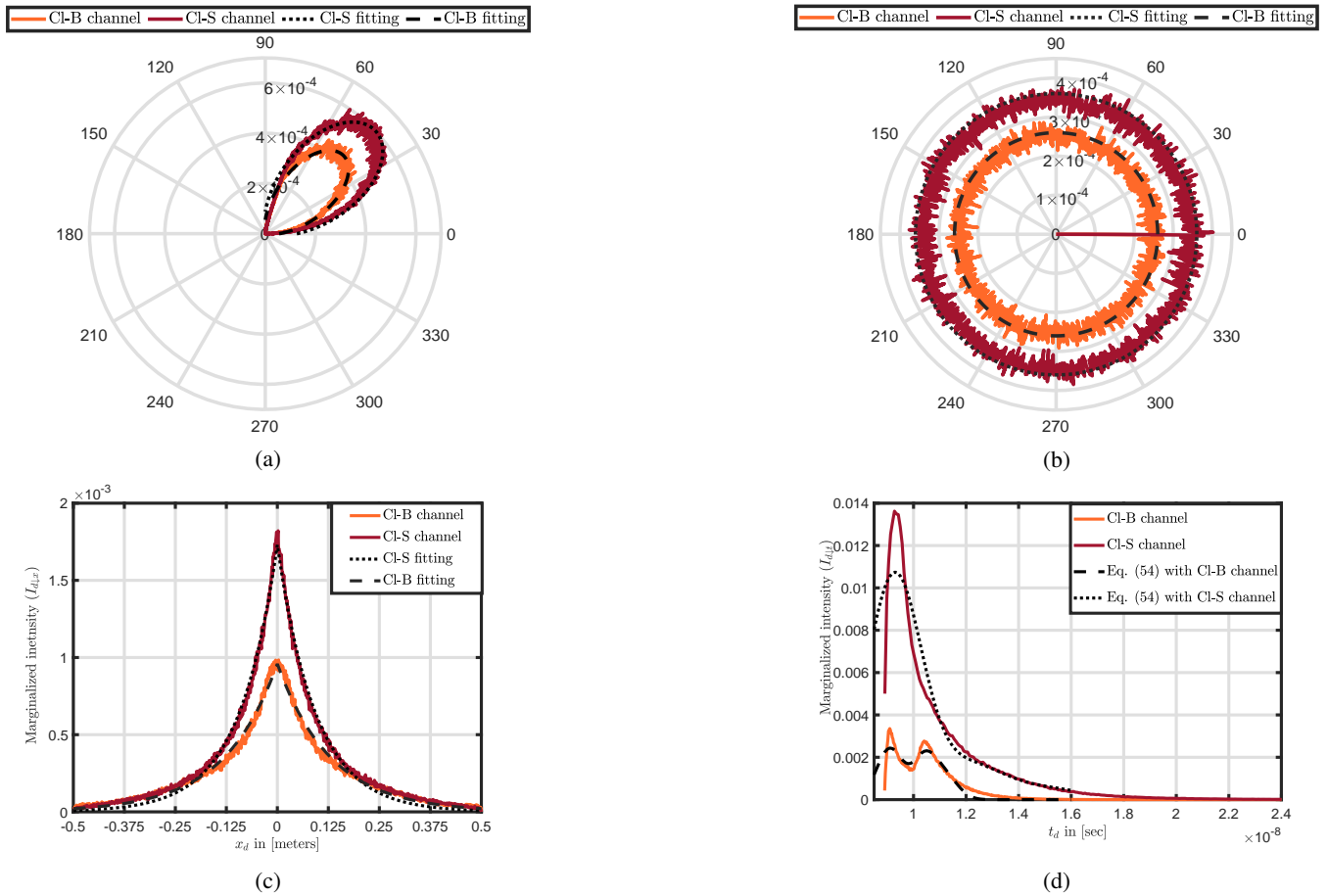


FIGURE 6: The marginalized diffusing patterns (a) $I_{d\downarrow\theta}(\theta_d)$, (b) $I_{d\downarrow\phi}(\phi_d)$, (c) $I_{d\downarrow x}(x_d)$, and (d) $I_{d\downarrow t}(t_d)$. The results are shown with the orange and maroon colors for the CI-B and CI-S channels, respectively. The fitted curves are indicated in black dashed and dotted lines for the CI-B and CI-S channels, respectively.

815 shown time dispersion patterns can be fitted to a sum of
816 Gaussian functions in t_d as¹⁵

$$I_{d\downarrow t}(t_d) = \sum_{i=1}^3 \alpha_i \exp\left(-\left(\frac{t_d - \beta_i}{\gamma_i}\right)^2\right). \quad (53)$$

817 Equations (51)-(53) serve as a guide for a future analytic
818 model for the upward transmission. The equations are shown
819 with dotted lines in Fig. 6. We notice a good agreement
820 between the equations and MCNRT results in space but less
821 accuracy for the temporal dispersion patterns. Note that we
822 also tested other fitting functions proposed in the literature for
823 underwater CIRs in other scenarios (such as double gamma
824 weighted [87], combination of exponential and arbitrary
825 power [88], and Beta Prime distributions [89]), however,
826 Eq. (53) provided a much better in fit for SDOC. In fact,

¹⁵For CI-B channel, the coefficients α_i , β_i and γ_i are $\{2.405 \times 10^{-3}, 1.931 \times 10^{-3}, 1.025 \times 10^{-3}\}, \{9.093 \times 10^{-9}, 1.041 \times 10^{-8}, 1.121 \times 10^{-8}\}, \{7.041 \times 10^{-10}, 6.492 \times 10^{-10}, 7.043 \times 10^{-10}\}$, respectively. As well, For CI-S channel, the coefficients α_i , β_i and γ_i are $\{1.059 \times 10^{-2}, 1.547 \times 10^{-3}, 5.333 \times 10^{-4}\}, \{9.274 \times 10^{-9}, 1.206 \times 10^{-8}, 1.492 \times 10^{-8}\}, \{1.465 \times 10^{-9}, 1.817 \times 10^{-9}, 2.262 \times 10^{-9}\}$, respectively.

827 the fitting is challenging due to the dense scattering taken
828 place in the channel. Thus, further investigation is required
829 to obtain more accurate equation as a future work.

B. RESULTS FOR DOWNWARD TRANSMISSION

830 In this subsection, we demonstrate numerical results for the
831 CIR, DC gain H_o , and the delay spread τ_{RMS} . The results are
832 obtained using equations (34)-(37), and take into account the
833 effects of the type of the sea ice, seawater, Rx configuration,
834 and the position of the AUV-Rxs. The position and FOV
835 parameters in the following were chosen to show there scope
836 of operating characteristics for the SSCL channel. The opti-
837 mization of these parameters for maximize communication
838 performance is left as future work.
839

1) Impact of Sea Ice

840
841
842 Figures 7 shows the normalized received power versus ar-
843 rival time (i.e., CIR) for the case of coastal seawaters and
844 different types of ice sheet, namely, Co-S, Co-B and coastal-

pure (Co-P)¹⁶ channels. The AUV-Rx has the parameters $\theta_{FOV} = 140^\circ$ and $D_r = 15$ cm, and is located at the position $(\Delta_x = 2, \Delta_y = 0, \Delta_z = 3)$ m. As shown in the figure, the snow-covered sea ice sheet records the highest CIR amplitude and the largest dispersion thanks to the dense scattering occurring through its layers, as given in Table 2b. The Co-B channel shows a lower CIR amplitude and a relatively narrow dispersion due to a lower scattering coefficient as compared to the Co-S channel, see Tables 2a and 2b. The CIR of the pure sea ice sheet channel records the smallest amplitude and dispersion because there are no particles to scatter from inside the sheet. This result is likely to arise when the sea ice is thinned, such as when a part of the sea ice sheet melts in the summer season. The channel time delay, τ_d , takes its smallest value in the case of Co-S channel, which due to the fact that the second layer in the Co-S channel ($m = 2$) has a larger scattering coefficient with contrast to the second layer in the Co-B channel, see Tables 2b and 2a. Numerically, the peaks of the CIRs are 3.1×10^{-6} , 2.4×10^{-6} and 3.2×10^{-8} , and the delay spreads are 15×10^{-9} , 8×10^{-9} and 4×10^{-9} sec for the Co-S, Co-B and Co-P SSCL channels, respectively.

2) Impact of Seawater

Figure 8 shows the CIR for an AUV-Rx with $\theta_{FOV} = 90^\circ$ and $D_r = 15$ cm at position $(\Delta_x = 3, \Delta_y = 0, \Delta_z = 2)$ m bellow a bare sea ice sheet. The CIRs are shown for the Co-B, Cl-B and a Pu-B SSCL channels, where Pu-B denotes pure seawater cascaded with the bare sea ice sheet¹⁷ (i.e., $a(m = 1) = 0.053 \text{ m}^{-1}$, $b(m = 1) = 0.003 \text{ m}^{-1}$) [64]. Here, we used the bare-sea ice which has less scattering compared to snow-covered sea ice, this makes the effect of the seawater on the channel more significant. At a distance of $\Delta_x = 3$ m from the AUV-Tx, the FOV does not see the diffusing spot on the bottom of the sea ice. Thus, the amplitude of the CIR depends on beam scattering in the sea water. As shown in the figure, the case of coastal seawater has the highest amplitude and largest dispersion due to particle scattering. However, pure seawater provides the AUV-Rx with the less significant CIR. Numerically, the peaks of the CIRs are 5.2×10^{-9} , 3.4×10^{-9} and 2×10^{-10} , as well, and the delay spreads are 8×10^{-9} , 8×10^{-9} and 4×10^{-9} sec for the Co-B, Cl-B, and P-B SSCL channels, respectively.

3) Effects of FOV

Figure 9 shows the DC gain and delay spread of the channel versus the Rx FOV for AUV-Rx located at position $(\Delta_x = 3, \Delta_y = 0, \Delta_z = 2)$ m. In general, increasing the FOV leads to the collection of more rays and improves the DC gain. However, the rate of change in the DC gain with the FOV

¹⁶Co-P SSCL channel is the coastal seawater cascaded with a free-impurity sea ice, i.e., a perfect transparent sea ice. This pure sea ice rarely exists on the frozen oceans, and it is considered here just as benchmark.

¹⁷The pure seawater rarely exists underneath the frozen oceans, and it is considered here for comparison.

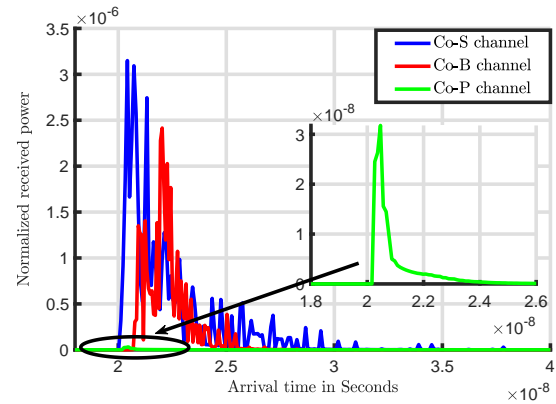


FIGURE 7: The effects of the sea ice on CIR with $(\theta_{FOV} = 140^\circ, D_r = 15 \text{ cm})$ and position $\{\Delta_x, \Delta_y, \Delta_z\} = \{2, 0, 3\}$ m.

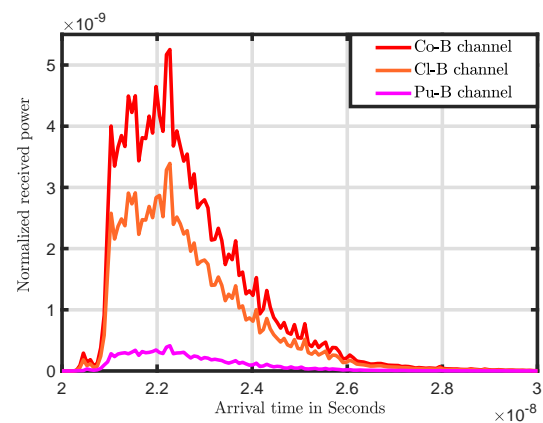


FIGURE 8: The effects of the seawater on CIR with $(\theta_{FOV} = 90^\circ, D_r = 15 \text{ cm})$ and position $\{\Delta_x, \Delta_y, \Delta_z\} = \{3, 0, 2\}$ m.

$(\partial h_o / \partial \text{FOV})$ depends on the location of the AUV-Rx with respect to the diffusing surface. For the given case study in Fig. 9 and according to the geometry of the topology, the receiver aperture begins to receive a direct signal from the diffusing surface at a computed $\text{FOV} = 102.7^\circ$ and receives signals from the complete diffusing surface at a computed $\text{FOV} \geq 120.5^\circ$. The computed FOVs are shown in the figure with values 93° and 122° , respectively, due to the impacts of the orientation of the diffusing beam with angle 45° and scattering occurring in the coastal seawater. This observation can help explain the results given in the figure as follows. When the FOV changes from 36° to 93.6° , the rate of change in $\partial h_o / \partial \text{FOV}$ is 0.0456 per degree. As the FOV increases further, it starts to collect rays with high energy from the diffusing surface. Thus, when the FOV changes from 93.6° to 122° , the rate of change increases to $\partial h_o / \partial \text{FOV}$ is 0.2137 per degree. Increasing the FOV further ($\text{FOV} \geq 122^\circ$), there is no additional improvement in the DC gain since nearly all power is collected.

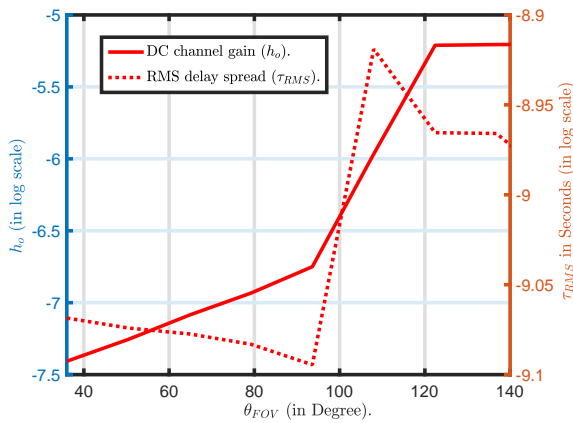


FIGURE 9: The effects of the FOV on h_o and τ_{RMS} with $D_r = 10$ cm at position $\{\Delta_x, \Delta_y, \Delta_z\} = \{3, 0, 2\}$ m and Co-B channel.

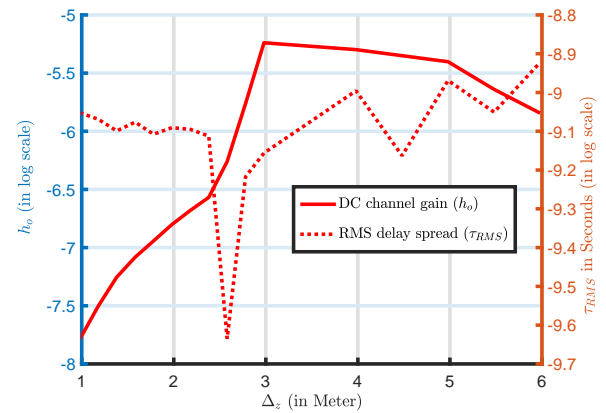


FIGURE 10: The effects of the depth on h_o and τ_{RMS} with ($D_r = 10$ cm, $\theta_{FOV} = 90^\circ$) at x-y position $\{\Delta_x, \Delta_y\} = \{3, 0\}$ m and Co-B channel.

On the other hand, the RMS delay spread depends on the time of diffusing t_d (20) in addition to the time taken to propagate from the bottom of the sea ice to the lens of the Rx (i.e., the distance $\mu_{d_o} + \mu_{d_1}$, see Fig. 4). In general, the value of t_d is a smaller for diffused rays that leave the sea ice close to the origin of the diffusing spot than for those rays that are further away. However, the propagation time from the sea ice to Rx for rays near the diffusing spot is longer than those further away. The RMS delay spread of the link is thus impacted by the balance of diffusing and propagation times. Qualitatively, when $\theta_{FOV} \leq 97^\circ$, the Rx does not see the diffusing spot origin directly and the RMS delay spread is dominated by t_d . That is, the total time of propagation will be close to the mean value resulting in a smaller RMS delay spread. However, as FOV increases, i.e., $97^\circ \leq \theta_{FOV} \leq 107^\circ$, the received rays from the diffusing spot with longer propagation time dominate increasing the delay spread. Finally, for $\theta_{FOV} \geq 107^\circ$, the AUV-Rx receives diffused rays arriving from both the origin of the diffusing spot, $\{x_d, y_d\} \approx 0$, as well as diffused rays over a wider area of the ice sheet which contributes to a reduction in the delay spread.

4) Impact of Depth

Figure 10 shows the DC gain and delay spread of the channel versus the depth, Δ_z , for an AUV-Rx with lens diameter $D_r = 10$ cm and $\theta_{FOV} = 90^\circ$. The AUV-Rx is located at a relatively long distance from the origin of the sea ice, ($\Delta_x = 3$ m, $\Delta_y = 0$) m. The AUV-Rx captures more diffused rays with increasing depth in the range $\Delta_z = [1, 3]$ m, then, the power captured decays with range for $\Delta_z \geq 3$ m, as shown. This phenomena can be interpreted as follows. The spatial coverage of the diffusing pattern, in the $x-y$ plane, extends with the depth due to two reasons. Firstly, the orientation of the diffusing pattern with the polar angle

as shown in Fig. 6a. Secondly, the scattering taking place in coastal seawater contributes more in extending the spatial coverage of the diffusing pattern. However, for $\Delta_z \geq 3$ m, the DC gain decays with the depth, due to the absorption taking place in the coastal seawater which dominates the impact of scattering. Numerically, the rate of change in the gain with the depth, ($\partial h_o / \partial(\Delta_z)$), is fixed in the range $\Delta_z = [1.5, 2.5]$ m with value $\partial h_o / \partial(\Delta_z) = 0.6860$ per meter, however, it is higher in the range $\Delta_z = [2.5, 3]$ m with value $\partial h_o / \partial(\Delta_z) = 2.1419$ per meter. On the other hand, the delay spread reaches to its minimum value at depth $\Delta_z = 2.7$ m as shown. This occurs since the lens (with $\theta_{FOV} = 90^\circ$ and at location $\Delta_x = 3$) captures the LOS rays diffused from points close to the diffusing spot on the bottom of the sea ice. These LOS rays arrive with high amplitude and small propagation times, resulting in the RMS delay spread attaining its minimum value.

5) The Spatial Distributions of H_o and τ_{RMS}

Figure 11 shows the spatial distributions of the DC channel gain and the RMS delay spread versus the position of the AUV-Rx in the $x-y$ plane. The results are shown for Co-S channel within the area of 6×6 m². As well, Table 3 summarizes statistical values of the DC and RMS delay spread and contrasts the results with the case of the Co-B channel. The results are associated to an AUV-Rx located at $\Delta_z = 3$ and equipped with a lens with $D_r = 15$ and cm, $\theta_{FOV} = 140^\circ$. These settings for the AUV-Rx are used in the remainder of the numerical results.

As shown in Fig. 11a, the DC gain distribution is symmetric in the $x-y$ plane around the center ($\Delta_x = 0, \Delta_y = 0$) and the DC gain value decreases monotonically with Δ_x and Δ_y . The shown distribution matches with the average response from the results in Figs. 6b and 6c. As well, as given in the table, the DC gain values in case of the Co-S channel are

TABLE 3: Extracted statistics from Fig. 11

Parameters	The Co-S channel	The Co-B channel
Minimum h_o	5.82×10^{-6}	6.2×10^{-6}
Maximum h_o	1.239×10^{-4}	0.7×10^{-4}
Average h_o	3.587×10^{-5}	2.33×10^{-5}
Minimum τ_{RMS}	8.74×10^{-10}	5.50×10^{-10}
Maximum τ_{RMS}	1.53×10^{-9}	1.085×10^{-9}
Average τ_{RMS}	1.073×10^{-9}	0.77×10^{-9}

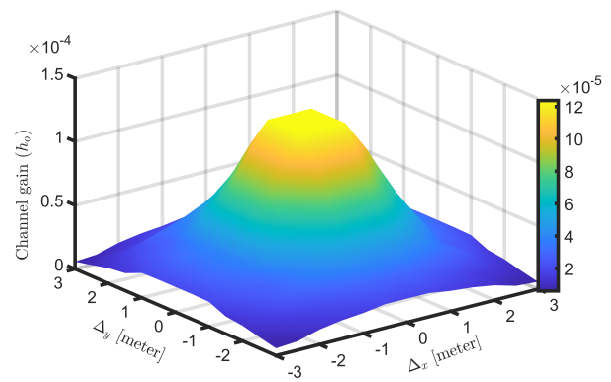
983 higher than that in case of the Co-B channel due to the dense
 984 scattering taking place in the snow cap. Numerically, from
 985 Table 3, the maximum values of the DC gain are 0.7×10^{-4}
 986 and 1.239×10^{-4} and the average values are 2.33×10^{-5} and
 987 3.587×10^{-5} for the Co-B and Co-S channels, respectively.

988 In Fig. 11b, the RMS delay spread spatial distribution is
 989 shown. In the area under the diffusing surface, the main
 990 amount of the power arrives from the LOS rays from the
 991 diffusing spot. Thus, these rays take the shortest path and
 992 the corresponding RMS delay spread has the lowest value
 993 in this area. At the edge of the considered area, the major-
 994 ity of received power arises from scattered rays. Thus, the
 995 corresponding RMS delay spread has the highest value. In
 996 the intermediate area, the RMS delay spread value fluctuates
 997 with the position of the AUV-Rx depending on whether a
 998 LOS or scattering components dominate. As well, from Table
 999 3, the RMS delay spread is on the order of nanoseconds,
 1000 however, the values in case of the Co-S channel are higher
 1001 than that in case of the Co-B channel. Numerically, the
 1002 maximum values of the RMS delay spread are 1.085×10^{-9}
 1003 s and 1.53×10^{-9} s and the average values are 0.77×10^{-9}
 1004 s and 1.073×10^{-9} s for the Co-B and Co-S channels,
 1005 respectively.

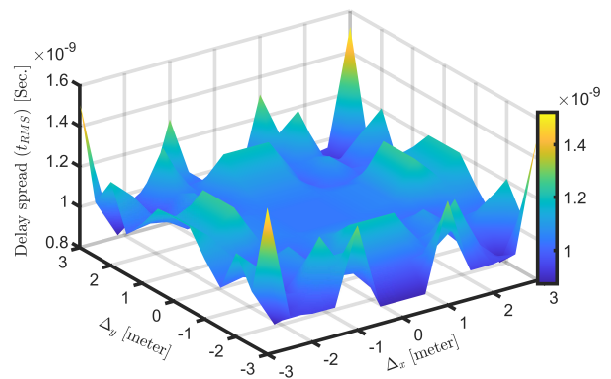
1006 C. LINK PERFORMANCE

1007 In this subsection, we numerically investigate the BER per-
 1008 formance and maximum achievable bit rate for proposed
 1009 system. The AUV-Rx is equipped with $D_r = 15$ cm with
 1010 $\theta_{FOV} = 140^\circ$ and located at y - z position $\{\Delta_y, \Delta_z\} =$
 1011 $\{0, 3\}$ m, load resistance is $R_L = 200 \Omega$, and the electrical
 1012 bandwidth of the Rx is considered as 0.7 GHz. A DFE
 1013 equalizer is implemented using 15 taps T_b -spaced branches.
 1014 The coefficients of the taps are obtained using 2024 training
 1015 symbols, and the LMS algorithm runs with control value
 1016 equal to 0.15. The ISI, shot, and thermal noises are evaluated
 1017 using Eqs. (44)-(48). For the background radiation, clear
 1018 weather is assumed with the sun at zenith angle equal to
 1019 $\approx 60^\circ$ [72], [82]. For the thermal noise, the temperature of
 1020 the seawater is assumed zero Celsius, see Fig. 2.

1021 Figure 12 shows the average BER performance versus the
 1022 distance Δ_x for a perfect equalizer receiver (Rx-PE), i.e.,
 1023 $v_{isi} = 0$, where performance limitation only arises from
 1024 the Rx noise, dominated by background radiation. Here, we
 1025 consider Co-B and Co-S channels, and the RxS are equipped
 1026 with optical filters with bandwidths $\Delta\lambda \in \{1, 5, 10\}$ nm.
 1027 The average transmitted optical power is $P_o = 100$ mW
 1028 and the bit rate is $R_b = 50$ Mbps. As shown, the BER



(a)



(b)

FIGURE 11: The distributions of h_o and τ_{RMS} with ($D_r = 15$ cm, $\theta_{FOV} = 140^\circ$, $\Delta_z = 3$) for the Co-S channel.

1029 performance degrades with distance and improves by de-
 1030 creasing the bandwidth of the optical filter. As well, the BER
 1031 performance in the case of the Co-S channel is better than
 1032 Co-B channel for two reasons. Firstly, the Co-S channel has
 1033 a higher upward transmission DC gain; secondly, the Co-S
 1034 channel reduces impact of the solar radiations much more
 1035 than the Co-B channel. For example, considering a BER
 1036 threshold of 10^{-3} as indicated by the green line in the figure,
 1037 the AUV-Tx can communicate with the Rx-PE at ranges
 1038 $\Delta_x = \{4, 3, 2.75\}$ and $\{3.5, 2.75, 1\}$ m with the bandwidth
 1039 $\Delta\lambda = \{1, 5, 10\}$ in cases of the Co-S and Co-B channels,
 1040 respectively. In other words, scaling $\Delta\lambda$ down by 10 times
 1041 raises the communication range by 45% and 250% in cases
 1042 of Co-S and Co-B channels, respectively.

1043 Figure 13 compares the normalized optical power penalty
 1044 (NOPP) versus the normalized RMS delay spread (NRDS)
 1045 defined as

$$NRDS = \frac{\tau_{RMS}}{T_b}$$

1046 at BER= 10^{-3} for receivers with equalization (Rx-E) and
 1047 unequaled (Rx-UE). The NOPP is defined as the required
 1048 transmitted optical power to achieve the desired FEC limit
 1049

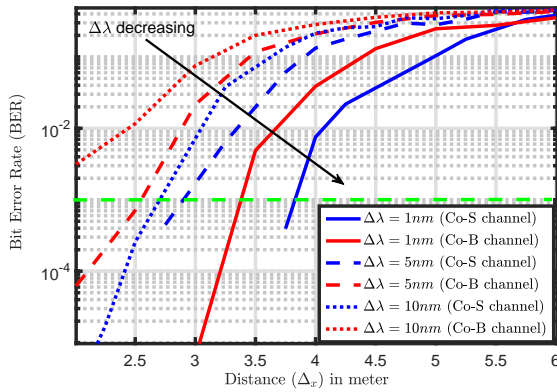


FIGURE 12: The BER for the Rx-PE (perfect equalization) system versus the distance x with $R_b = 50$ Mbps and $P_o = 100$ mW.

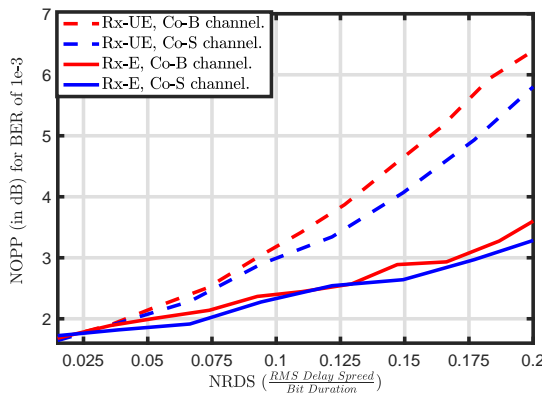


FIGURE 13: The normalized optical power penalty (NOPP) versus the normalized RMS delay spread (NRDS) for Rx-E and Rx-UE (no equalization) cases.

in cases of Rx-E and Rx-UE systems normalized by that required in case of the Rx-PE system. The RMS delay spread τ_{RMS} is computed for the AUV-Rx at position $\Delta_x = 2$ m, where $\tau_{RMS} = 1.1 \times 10^{-9}$ s and 8.5×10^{-10} s for the Co-S and Co-B SSCL channels, respectively. As well, the bit duration is varied in the range $T_b \in [2, 100]$ ns, i.e.,¹⁸ $R_b \in [10, 500]$ Mbps. The case of Rx-UE is used as a benchmark to highlight the benefit of channel equalization.

At low data rates, e.g., (NRDS ≤ 0.05), where the bit duration is much larger than the RMS delay spread, the effect of ISI on the system performance is limited and the performance of Rx-UE and Rx-E are nearly the same. As the data rate increases, the impact of ISI increases and Rx-E gradually outperforms Rx-UE. Specifically, for the Co-B channel at NRDS= 0.075, Rx-E and Rx-UE require NOPP= 2.15 dB and NOPP= 2.52 dB, respectively. For the Co-S channel at

¹⁸At distance $\Delta_x = 2$ m, a data rate of 500 Mbps is considered as a maximum since the average transmitted power is limited to 200 mW for the Rx-E systems, as indicated in the simulation parameters.

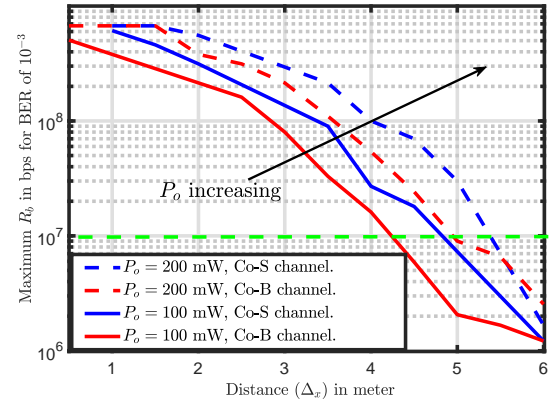


FIGURE 14: The maximum achieved bit rate for the Rx-E system versus the distance with FEC limit of BER= 10^{-3} .

the same NRDS, Rx-E and Rx-UE require NOPP= 2 dB and NOPP= 2.5 dB, respectively. At higher data rates of NRDS= 0.2, Rx-E and Rx-UE require NOPP= 6.3 dB and NOPP= 3.5 dB, respectively, for the Co-B channel. For the Co-S channel at the same NRDS, Rx-E and Rx-UE require NOPP= 3.2 dB and NOPP= 5.8 dB, respectively. These results indicate that the equalizer improves the power efficiency of the systems by nearly 3 dB, which means the required transmitted power is reduced roughly by a factor of two. In other words, the AUV with the equalized system enhances the power-efficiency of the AUVs which means more lifetime for the battery.

Figure 14 shows the maximum achievable bit rate under the constraint $BER \leq 10^{-3}$ versus the distance Δ_x with average transmitted optical power $P_o \in \{100, 200\}$ mW. As shown in the figure, the maximum achievable bit rate ($R_b \approx 700$ Mbps) is achieved directly under the diffusing surface ($\Delta_x \leq 1$ m). However, as Δ_x increases, the maximum achievable bit rate decreases; the proposed system can achieve broadcast data rates on the order of $R_b = 1$ Mbps over communication ranges of $\Delta_x = 6$ m. As indicated by the green dashed line, to maintain a communication rate of 10 Mbps, scaling the transmitted power by 2 increases the communication range by 18% and 10% in cases of Co-B and Co-S channels, respectively. This trade off between data rate and coverage distance should be considered during planning stage of the AUV swarms, based on the required data rate and range.

VI. CONCLUSIONS

In this paper, for first time, we propose a broadband-broadcast approach suitable for networking AUVs under sea ice, albeit with limited range. We take advantage of existing ice sheets on the sea surface to establish a diffusing communication systems. The SSCL model was introduced in which the channel is represented in the form of cascaded layers with uniform optical characteristics. Due to the challenge of analytic modeling of optical signal scattering inside the ice sheet, MCNRT is used to evaluate the diffusing pattern of

upward transmission. For downward transmission, the CIR was derived in the form of a quasi-analytic equation assuming single scattering light propagation. Due to the expected effects of ISI and relatively high background solar power noise, we propose a new transceiver architecture that helps in mitigating the effects of these factors. We also provide extensive numerical results to investigate the effects of water and ice types, Rx parameters i.e., FOV and optical filter bandwidth, and the Rx location on the system performance.


The challenges in implementing SDOC systems includes the transceiver size which must be carefully chosen depending on the size of the AUV. The transmitted power must also be determined according to battery-life and eye-safety constraints. Lastly, the SDOC approach is not appropriate bellow transparent sea ice sheets which rarely exist in practice on frozen oceans. Future work includes further investigations for quasi-analytic forms of the diffusing patterns, investigating a better fit for the temporal diffusing pattern as well as experimental validation of the obtained results.

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