Underwater Localization using Airborne Visible Light Communication Links

Jaeed Bin Saif, and Mohamed Younis
Department of Computer Science and Electrical Engineering
University of Maryland Baltimore County
Baltimore, Maryland, USA
jaeedb1, younis@umbc.edu

***Abstract*—Localization of underwater networks has received lots of attention. However, existing scheme focuses on establishing a relative topology where a node's position is defined in relation to one another. Provisioning global coordinates is achieved only through the inclusion of a surface node that can serve as a reference. This paper opts to tackle the global localization problem in setting where surface nodes cannot be deployed or should be avoided. Our approach is to establish visible light communication (VLC) links across the air-water interface. An airborne unit is to transmit its GPS position using VLC. Upon receiving such a message, the underwater node will factor in the light intensity and coverage to determine its own position relative to the airborne node and consequently its own GPS coordinates. The simulation results demonstrate the effectiveness of our approach and high positioning accuracy.**

Keywords*— *Underwater localization; Visible light communication.

I. INTRODUCTION

Underwater networks have attracted attention due to their numerous applications that cross many domains. Example applications include underwater security surveillance, search and rescue missions, sea-based combat, marine biology, pollution monitoring, etc. In these applications, underwater nodes are usually inter-connected to terrestrial entities, e.g., command centers, by means of afloat nodes that serve as gateways. These surface nodes often use radio waves to interact with remote centers; yet they use acoustic signals to communicate with underwater nodes [1]. Basically, penetration of RF signals of the water surface is quite low because of their high absorption coefficient in water. Hence the gateway node switches to signals based on the medium and serves as a relay between nodes under and outside the water.

However, the presence of gateway nodes increases the complexity of network deployment and management, especially when node mobility is expected. For example, in a search-and-rescue setting, employing a gateway node constitutes a logistical burden as it has to be a mobile that can stay connected with the underwater nodes while they hover around and change positions. The presence of surface nodes can also hamper covert military applications as they are visible and can be tracked by adversaries to find hidden underwater equipment. Therefore, visible light communication is deemed a viable option for communication across the air-water interface [2]. Using VLC links not only eliminates the need for surface nodes, but also offers much higher communication channel bandwidth [3]. Prior work has characterized the properties of cross-medium VLC links [4] and proposed suitable modulation schemes [5]. Such work is being leveraged in this paper.

Localization of underwater nodes is very important establishing and maintaining a stable network topology. Particularly underwater nodes are either inherently mobile or just get drifted by water current; therefore, an underwater network can easily get partitioned and some nodes become unreachable. Knowing the position of nodes would enable tracking of nodes and mitigating the effect of mobility. Moreover, localization is critical for event monitoring and correlation. Not surprisingly, many localization methods have been proposed in the literature to fill the technical gap. However, existing techniques focus on establishing a relative coordinate system where the position of nodes is defined relative to one another rather than to a global coordinate system, such as GPS. The only means to provision global localization is to integrate surface nodes in the network and factor in their GPS coordinates. Again, the incorporation of surface nodes could be disadvantageous as noted above. Therefore, there is a need for an unconventional methodology for instrumenting a global positioning system for underwater networks.

This paper proposes an innovative localization scheme for localizing underwater nodes without the presence of surface-based reference nodes. We are leveraging the advantages of VLC to establish communication links across the air-water interface. We use an airborne unit to directly reach underwater nodes; the airborne unit broadcasts its GPS coordinates. We propose a novel algorithm for the underwater to determine its location when receiving the message of airborne units. Our algorithm factors in the light intensity and the optical transmission angle to correlate the underwater node's position to that of the airborne unit and consequently estimates GPS coordinates of the underwater node. Once a node is globally localized, it can also globally localize other sensor nodes within its network using traditional underwater localization methods. We evaluate the effectiveness of our approach through simulation. The simulation results show that our algorithm can achieve small localization errors and high percentages of localizable nodes. To the best of our knowledge, our approach is the first to provision GPS coordinates in underwater settings without the help of surface nodes.

This paper is organized as follows. In Section II, the related work is discussed. Section III covers the system model and describes the factors that affect the underwater light intensity when an VLC beam is directed to the water surface. Our approach for localizing underwater nodes is detailed in Section IV. Section V provides validation results using simulation. Finally, section VI concludes the paper.

II. RELATED WORK

In this paper, we focus on developing a localization method using VLC links in a cross-medium scenario. Since acoustic communication is usually considered as the standard method of underwater environment [1], most existing underwater localization methods are acoustics based [6]-[8]. However, acoustic links have severe data rate limitation caused by the small frequency band and the high signal attenuation while traveling in underwater environments [9]. Moreover, the use of underwater acoustics enables range estimation between nodes and the establishment of a relative coordinate system; hence, surface nodes are used to correlate the underwater node position to a global reference. A cross-medium communication solely using acoustic methods would not alleviate the need for surface nodes since the acoustic signal suffers high attenuation in air as well. No localization scheme has been proposed in the literature to eliminate the need of an inter-medium gateway node.

VLC provides higher bandwidth (Mb/s to Gb/s) in water than acoustics-based methods (kb/s) [10][11]. In recent years, underwater VLC has been extensively investigated. Published studies include channel modeling [12][13], performance evaluation [14], etc. Yet, the scope is limited to the use of visible light solely in the water medium. This paper leverages the advantages of VLC over acoustics, like high cross-medium penetration and high bandwidth, in order to localize underwater nodes and instrument global coordinates without the use of surface nodes. Some recent studies, e.g., [4], have characterized the cross-medium performance of VLC. Prior work has also been done on modulating the light signal for cross-medium communication [5]. Analyzing optical behavior in different water conditions or types, have been the focus of multiple studies [15][16]. Although VLC has been exploited in in-door localization [17] and on-road inter-vehicle proximity [18], to our knowledge, no published research has addressed underwater localization using VLC links and providing direct GPS location of an underwater node without any inter-medium gateway node.

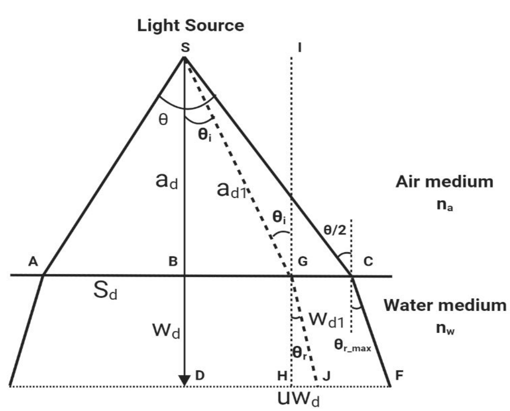


Fig. 1: A 2-D illustration of the coverage of light transmission from a source at *S* above the water surface.

III. SYSTEM MODEL AND BACKGROUND

A. System Model and Assumptions

The underwater nodes are scattered across an area of interest. The airborne node initiates transmission through a visible communication link using visible light and the underwater node receives the transmission. The airborne node is equipped with a GPS to get the global positioning of itself. The underwater node is assumed to be equipped with optical/light sensor and pressure sensor. The optical sensor tells the underwater node the amount of light it is receiving, and the pressure sensor is conveying the information of the underwater node depth from the water surface. Though the water surface is assumed to be flat, the underwater node can be displaced from one position to another due to water current. This phenomenon is called node drift.

Given the potential node drift, the boundary of the deployment area varies over time; therefore, the airborne unit may potentially cover a large area. One or multiple airborne units may be employed in order to expedite the coverage process. An airborne node uses VLC transmissions to reach underwater nodes. For this purpose, we are using a light source with known beam angle and known distance from the water surface. We are considering a LED source as a light source since it can generate directional beam with controllable beam angle using optics.

B. Light Intensity and Underwater Coverage

In [4], the underwater coverage and intensity of an airborne light source are analyzed. We provide a summary of such an analysis since it is the basis for the proposed underwater localization scheme. Particularly, we discuss the relationship between light intensity within the coverage area and how to varies with depth. Table I provides a summary of the used notation. Fig. 1 shows the propagation of light beam through air and water in a two-dimensional surface, assuming free space optics and flat water surface. Assuming that a light source is located at *S* with a beam angle of θ. The source is a_d meter above the surface of the water and the underwater sensor is w_d meters below the water surface, we can calculate coverage of light on the surface of water:

$$\overline{AC} = 2a_d \, . tan\frac{\theta}{2} \tag{1}$$

$$\overline{BC} = \overline{BA} = a_d \, . tan\frac{\theta}{2} \tag{2}$$

TABLE I. DEFINITION OF THE USED NOTATION

Notation	Description
P	Power of the light source
θ	Beam angle of the light source for flat surface
θ_i	Incident angle of water surface for flat surface
θ_r	Refraction angle for flat surface
a_d	Distance of light source from water surface for flat surface
w_d	Depth of the sensor from water surface for flat surface
η	Reflectance of light
τ	Transmittance of light

We can apply Snell's law to calculate coverage area underwater. Assuming the refractive index of air and water are n_a and n_w respectively, at point *C*:

$$\frac{n_a}{n_w} = \frac{\sin\theta_{r\_max}}{\sin\theta/2} \tag{3}$$

For a light beam at point *G*, the incident angle is θ_i and refractive angle under water is θ_r.

$$\angle SGI = \angle BSG = \theta_i \tag{4}$$

$$\overline{BG} = a_d \,.\tan\theta_i = \overline{DH} \tag{5}$$

We can calculate refractive angle for point *G* using Snell's law and use to determine $\overline{DH}$ and $\overline{DJ}$.

$$\theta_r = \frac{n_a}{n_w}\,.sin\theta_i \tag{6}$$

$$\overline{HJ} = w_d \,.\tan\theta_r \tag{7}$$

$$\overline{DJ} = \overline{DH} + \overline{HJ} \tag{8}$$

J is the point where the refracted light beam will reach underwater at uw_d distance. The light beam travels a_{d1} and w_{d1} in air and water, respectively, which can be calculated as below:

$$a_{d1} = \frac{a_d}{\cos\theta_i}, \qquad w_{d1} = \frac{w_d}{\cos\theta_r} \tag{9}$$

After travelling a_{d1} distance the light intensity will be:

$$I_{air} = \frac{360}{\theta}\cdot\frac{P}{4\pi a_{d1}^2} \tag{10}$$

We calculate light intensity I_{water} just below the water surface based on the transmittance τ, where $\tau = 1 - \eta$

$$I_{water} = I_{air}\,.\,\tau = I_{air}\ (1 - \eta) \tag{11}$$

The reflectance coefficient of light should be calculated for s- polarization and p-polarization, using Fresnel equation.

$$\eta_s = \left|\frac{n_a cos\theta_i - n_w cos\theta_r}{n_a cos\theta_i + n_w cos\theta_r}\right|^2 \tag{12}$$

$$\eta_p = \left|\frac{n_a cos\theta_r - n_w cos\theta_i}{n_a cos\theta_r + n_w cos\theta_i}\right|^2 \tag{13}$$

$$\eta = \frac{\eta_s + \eta_p}{2} \tag{14}$$

If the attenuation coefficient is k, for travelling w_{d1}distance the light intensity at point *J* is:

$$I = I_{water}\,.\,e^{-kw_{d1}} \tag{15}$$

Considering Eq. (9), (10), (11), and (15), the final intensity at point *J* with respect to the light source is:

$$I = \frac{360}{\theta}\,.\,\tau\,.\,\frac{P}{4\pi\left(\frac{a_d}{cos\theta_i}\right)^2}\,.\,e^{\frac{-kw_d}{cos\theta_r}} \tag{16}$$

C. Position within Coverage Area

Fig. 1 shows two-dimensional representation of the beam propagation. Since the light source is uniform, we can say that the full coverage area is circular on and under the water surface. Therefore, as shown in Fig. 2, we can say that intensity received by an underwater node will be same across the circumference of a circle since the distance from the center of coverage area is same for all points at specific depth. Since the water depth is known, we can assume the coverage area at that depth as a 2-D surface (x-y plane). Thus, by knowing θ_i, a_d and w_d, an underwater node will calculate corresponding θ_r and the distance from the center using Eq (5), (6), (7) and (8). Finally, using Eq (16) we can determine the intensity that corresponds to the measured distance. As the water surface is assumed to be flat, the light source's x-y coordinates and consequently the coordinate of the center of the coverage area can be calculated.

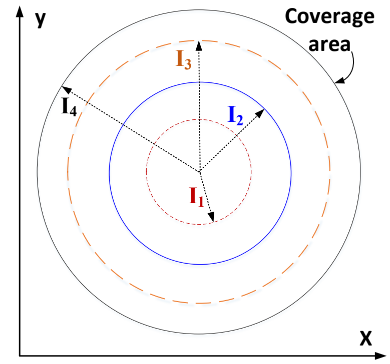


Fig. 2: Intensity distribution for a specific depth underwater

Finally we like to note that the attenuation coefficient k in Eq. (16) is the sum of absorption coefficient $a(m^{-1})$ and scattering coefficient $b(m^{-1})$. The value of a and b depends on the optical signal wavelength and water condition (presence of particles and biological entity). Four types of water have been considered in [15][16]. Table II shows the attenuation coefficient for different types of water.

TABLE II. TYPICAL COEFFICIENTS FOR DIFFERENT TYPES OF WATER

Water type	$a(m^{-1})$	$b(m^{-1})$	$k(m^{-1})$
Pure sea	0.053	0.003	0.056
Clean Ocean	0.114	0.037	0.151
Coastal Ocean	0.179	0.219	0.298
Turbid Harbor	0.295	1.875	2.17

IV. AIR-ASSISTED UNDERWATER LOCALIZATION

A. Design Goal and Ovaerall Methology

As pointed out earlier underwater nodes tend to drift due to water current or intentionally move to achieve a mission. Localizing the nodes is crucial from application perspective and for efficient management of the underwater network topology. This paper pursues a novel approach where reference points with known GPS coordinates can be introduced by an airborne unit. The latter employs modulated VLC transmissions to reach underwater nodes. By correlating its position to the GPS coordinates of the incident points on the water surface, an underwater node will be able to determine its own coordinates. The objective is to localize the maximum number of nodes with the most accuracy using minimum VLC transmissions.

An underwater node may be anywhere within the deployment area. To ensure reaching potentially all nodes, the airborne unit should cover the entire area. As pointed out in Section III, a VLC beam spreads in the air and refracts at a flat-water surface, forming a circular shape. Thus, achieving full area using the fewest transmissions is in essence a disc coverage problem that has been extensively investigated in the literature. It has been proven that the optimal solution for such a problem for a rectangular area is by titling using equilateral triangles with edge length of $\sqrt{3}\,r$, where is r is the radius of the disc [19]. In our context r depends on the targeted depth, as shown in Fig. 1. In such a case the airborne unit will target the vertices of the tiled triangles throughout the area. Fig. 3 shows an illustration. An interesting observation on Fig. 3 is that targeting the designated points will lead to double coverage, which is plausible; in fact, three-coverage may be necessary for estimating the coordinates of underwater nodes, as explained later in this section.

B. Airborne VLC Transmissions

As pointed out above, the entire deployment region is to be tiled and transmissions are to be initiated over corners of every single tile. Transmission over these smaller tiles can be initiated in several methods depending on the application of VLC. A single airborne node can consider tile by tile and cover the whole deployment area. Alternatively, several airborne nodes can sequentially cover all the tiles inside the deployment area. The drawback of using a single node to perform transmission over the whole deployment is that the total time to cover the whole area and conduct localization will be large and consequently the underwater node may also change its location slightly due to node drift underwater causing the localization error to grow. To reduce such a time, two options can be pursued:

(i) Limit the frequency airborne unit relocation by targeting the surface points (shown in Fig. 3) using tilted beams. Since a VLC beam that is normal to the surface will suffer the least reflection and losses, it is the most preferred in order to increase the reach to underwater nodes at increased depth. To avoid the latency due to excessive motion, the airborne unit can simply target the surface point at non-right angles at the expense of decreased coverage.

(ii) Employ multiple airborne nodes to cover the area, which requires synchronization among them. Close coordination among the airborne units would prevent redundant coverage, and transmission collisions where a node simultaneously becomes within the coverage area of multiple light m beams.

The validation of the proposed localization scheme will be mainly focused on assessing conventional metrics like accuracy and coverage. Optimizing the latency of the localization process is part of our future work plan. Each transmitted packet will also contain additional information such as the airborne node's GPS location, transmission power, height of the airborne node from the water surface, beam angle of the light source, and incident angle on the water surface. The same information about the transmission of the neighboring reference surface point (tile vertex). To localize the underwater node, the node itself needs to receive light from the airborne source so that node can be located based on the value of its received intensity. With each received transmission, based on the light intensity reading the underwater node knows its distance from the center of the coverage area. Since each transmission is broadcasting its GPS location, the underwater node can also determine its distance from the GPS location, since the center of the coverage area is the GPS location itself. If the beam is not normal to the surface, the underwater node has to calculate the normal component to estimate the actual power (and consequently the intensity) at the center of coverage area.

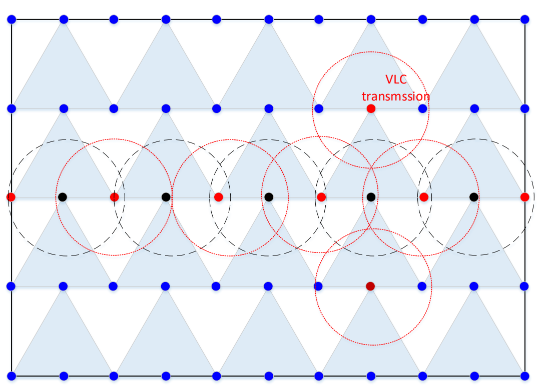


Fig. 3: Illustrating a titled deployment area marking the points targeted with directed VLC transmission from the airborne unit(s)

C. Underwater Position Determination

As shown in Fig. 3, the whole deployment area has been divided into smaller tiles. According to picked tiling, transmitting at each tile corner will achieve two-coverage if the airborne VLC beam is perpendicular on the water surface; hence each underwater node will be receiving two messages if it is at depth that is reachable by the allotted beam power and angle. Generally, the coverage area of each transmission will grow and the intensity will diminish by depth. Determining the right beam angle and power would practically depend on the operation depth of the underwater network. In order to maximize the power utilization, ideally, the airborne unit will vertically align with the surface reference point and transmit a modulated beam. Each consecutive transmission will repeat the process again. As each transmission is also broadcasting the information of the nearest transmissions as described earlier, the underwater node is aware of the transmissions that is missing which can be used for decreasing the location uncertainty in case insufficient transmissions are received.

As shown in Fig. 3, the transmission coverages overlap by appropriate tiling of the deployment region. If a node is receiving transmission through multiple reference points on the surface, it can determine its distance from each center of the coverage area. If it receives three or more transmissions, it can apply trilateration or multilateration to determine its exact location (Fig. 4(a)). If the node does not receive at least three transmissions from its position, it will apply area-based localization to narrow down its location [20]. When receiving

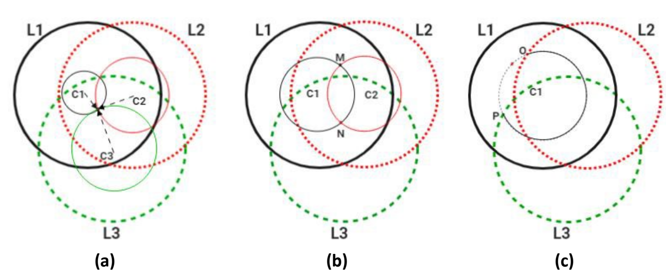


Fig 4. (a) localization for three received transissions (b) localization for two received transissions (c) localization for one received transission.

Algorithm 1: Air-assisted Underwater Localization

1. Divide of whole the deployment region into smaller tiles.
2. Make VLC of transmission at the corners of each tile; each transmission includes the GPS coordinate of the incident point on the water surface, the VLC parameters, e.g., power and angle, as well as the coordinates of the neighboring incident points on the surface.
3. Use the sensed intensity to determine proximity from the reference point on the surface.
4. If three or more transmissions are received, calculate the coordinates using trilateration or multilateration.
5. With only one or two received transmissions, determine the location by applying area-based localization techniques while factoring in missed transmissions through neighboring surface points.

two transmissions, two positions may be possible, shown as points *M* and *N* in Fig. 4(b). If the node is aware of the transmission at the neighboring surface points, it can eliminate *N* based on the fact that it did not receive transmission L3. Subsequently, if the underwater node receives one transmission only, it can narrow down its location on an arc OP shown in Fig. 4(c) and assume the centroid of the arc to its estimated position.

D. Performance Tuning

Generally, if a node receives only one transmission, the positioning precision will be low since the node may be located at any point on an arc rather than pinpointing a particular coordinate. In that sense, if the probability of receiving only one transmission is reduced, localization accuracy would also improve. This can be done by increased overlapping of the areas covered by the individual VLC transmissions. Growing the overlapped areas can be achieved by several ways, e.g., (i) by increasing the number of tiles in the same deployment region and using the same transmission power and beam angle; yet such a way will result in higher total transmission power and larger localization time. (ii) by keeping the same tile count and increasing the coverage area for each transmission through increased power, wider beamer angle, higher altitude of the airborne node. In all scenarios the intensity received by the underwater node will be decreased. By increasing the beam angle for the same transmission, it will spread out the same amount of light in a larger area thus the intensity decreases. Given the highlighted trade-off, deciding on the appropriate parameter setting will depend mostly on the underwater network operational depth, receiver sensitivity, and the capabilities of the airborne unit. Algorithm summaries the overall steps.

V. Approach Validation

A. Simulation Environment and Simulation Setup

We used MATLAB to validate our localization approach. We considered a light source of 100mw with a beam angle of 60 degrees. We assumed that the height of the airborne node from the water surface is 5 meters. Initially, we mapped the light intensity relative to its distance inside the coverage area at various depths (2m, 5m and 8m). In the second step of the simulation, we took a sample location area that has length and width of 10 meters and overlaid it with a four-cell grid. Then, we initiated transmission in such a manner that each tile was covered by at least one transmission. Light intensity is measured by the sensor for each transmission and according to the intensity mapping, sensor location is determined. We took 30 random points across the deployment area and determined the location of the sensor via the received transmissions. We have compared the results for pure seawater and turbid harbor water, since they respectively, have the least and most attenuation coefficients. We also compare with the performance of an acoustics-based localization scheme. We used the same setting to capture localization error for different numbers of surface anchor nodes. Although the parameters and conditions involving both methods are completely different, this has been done to show some possible comparison between the two methods.

B. Simulation Results

Fig. 5 depicts the percentage of localized nodes across various localization errors. Since in this graph we are considering optical sensors with no minimum sensitivity, the results for both pure seawater and turbid harbor water are identical. In both cases, localization performance is getting better as the depth increases. This is due to the growth of coverage area due to refraction and beam spreading underwater. Hence, the coverage area overlapping grows and the localization accuracy increases. To illustrate, the circles in Fig. 6 represent the coverage areas for each transmission and the rectangular area represents the deployment area. Fig. 7 shows the localization error for an acoustic method of localization. The simulation parameters like area size, and underwater node count, were kept as similar as possible to those of our approach. We used Thorp's equation to calculate the absorption coefficient and used a spherical spreading factor to simulate the environment [21]. Localization errors are shown for two different numbers of anchor nodes. Comparing the results on Figures 5 and 8, clearly

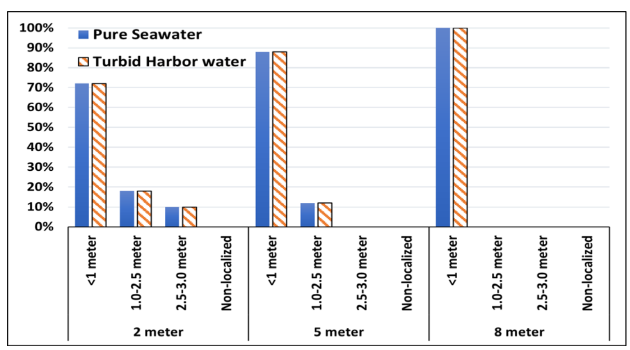
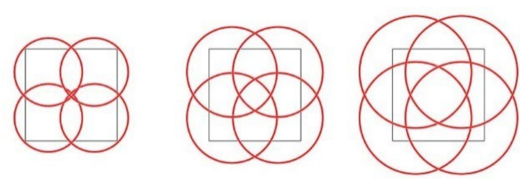


Fig. 5. Percentage of localized node vs localization error distance (m) for various depth and no minimum sensitivity of optical sensor in pure seawater, and turbid harbor water.



(a) **(b)** **(c)**

Fig 6. Comparison of coverage area at depth of: (a) 2 meters (b) 5 meters, and (c) 8 meters.

shows the advantages of our VLC-based approach, both in accuracy and localizatable node count.

For our proposed method, as the depth increases the overlapping areas with multiple transmissions also grows, resulting in improved localization performance. The attenuation coefficient for turbid harbor water is much higher than pure seawater. As light intensity decreases rapidly as the depth increases. The limitation in the optical sensor side will affect the localization error. Figure 8 represents localization error for three different values of minimum sensitivity of the optical sensor. As the sensitivity decreases, the localization performance diminishes for nodes at greater depth since they do not receive sufficient light due to higher attenuation coefficient.

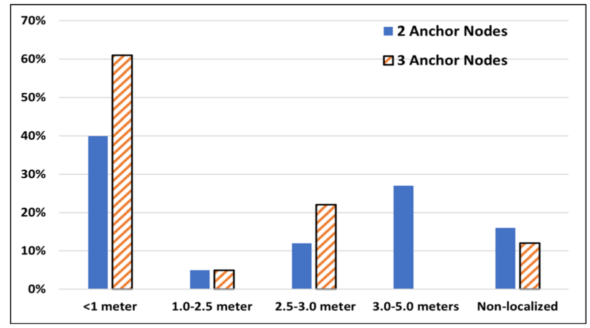


Fig 7. Percentage of node localized vs localization error distance (m) for two and three surface anchor node in acoustic localization method.

VI. Conclusion

This paper has presented a new approach of localizing and providing GPS coordinates to underwater sensor nodes using VLC link. Our method provides the benefits of not utilizing a surface gateway node which can be helpful in search and rescue, and military applications. The transmission pattern of airborne nodes has been studied to get optimum coverage and minimum localization error in the deployment area. The effectiveness of our approach has been confirmed through simulation.

Acknowledgment: This work is supported by the National Science Foundation, USA, Contract #0000010465.

Reference

[1] M. Jouhari, K. Ibrahimi, H. Tembine and J. Ben-Othman, "UnderwaterWireless Sensor Networks: A Survey on Enabling Technologies, Localization Protocols, and Internet of Underwater Things," *IEEE Access*, vol. 7, pp. 96879-96899, 2019.

[2] M. V. Jamali, A. Chizari, and J. A. Salehi, "Performance Analysis of Multi-Hop Underwater Wireless Optical Communication Systems," *IEEE Photonics Technology Letters*, vol. 29, no. 5, pp. 462-465, March 1, 2017.

[3] H. Kaushal and G. Kaddoum, "Underwater Optical Wireless Communication," *IEEE Access*, vol. 4, pp. 1518-1547, 2016.

[4] M. S. Islam, M. Younis and A. Ahmed, "Communication through Air Water Interface Using Multiple Light Sources," *Proc. IEEE International Conference on Communications (ICC)*, Kansas City, KS, June 2018.

[5] M. S. Islam and M. Younis, "An Adaptive DPPM for Efficient and Robust Visible Light Communication Across the Air-Water Interface," *Proc. of the 29th Wireless and Optical Comm. Conf. (WOCC)*, Newark, NJ, 2020.

[6] I. Ullah, J. Chen, X. Su, C. Esposito and C. Choi, "Localization and Detection of Targets in Underwater Wireless Sensor Using Distance and Angle Based Algorithms," *IEEE Access*, vol. 7, pp. 45693-45704, 2019.

[7] T. Islam and Y. K. Lee, "A Two-Stage Localization Scheme with Partition Handling for Data Tagging in Underwater Acoustic Sensor Networks," *Sensors*, vol. 19, no. 9, p. 2135, May 2019.

[8] J. Yan, D. Guo, X. Luo and X. Guan, "AUV-Aided Localization for Underwater Acoustic Sensor Networks with Current Field Estimation," *IEEE Trans. on Vehicular Tech.*, vol. 69, no. 8, pp. 8855-8870, Aug. 2020

[9] N. Li, J.-F. Martínez, J. Meneses Chaus, and M. Eckert, "A Survey on Underwater Acoustic Sensor Network Routing Protocols," *Sensors*, 16(3), p. 414, Mar. 2016.

[10] C. Shen et al., "20-meter underwater wireless optical communication link with 1.5 Gbps data rate," *Opt. Express*, 24(22), pp. 25502–25509, 2016.

[11] M. Kong et al., "10-m 9.51-Gb/s RGB laser diodes-based WDM underwater wireless optical communication," *Opt. Express*, 25(17), pp. 20829–20834, Aug. 2017.

[12] F. Miramirkhani and M. Uysal, "Visible Light Communication Channel Modeling for Underwater Environments with Blocking and Shadowing," *IEEE Access*, vol. 6, pp. 1082-1090, 2018,

[13] X. Ma, F. Yang, S. Liu, and J. Song, "Channel estimation for wideband underwater visible light communication: A compressive sensing perspective," *Opt. Express*, 26(1), pp. 311–321, Jan. 2018.

[14] M. Elamassie, F. Miramirkhani and M. Uysal, "Performance Characterization of Underwater Visible Light Communication," *IEEE Transactions on Communications*, 67(1), pp. 543-552, Jan. 2019,

[15] Y. Dong, S. Tang and X. Zhang, "Effect of Random Sea Surface on Downlink Underwater Wireless Optical Communications," in *IEEE Communications Letters*, vol. 17, no. 11, pp. 2164-2167, November 2013

[16] P. Saxena and M. R. Bhatnagar, "A Simplified Form of Beam Spread Function in Underwater Wireless Optical Communication and its Applications," *IEEE Access*, vol. 7, pp. 105298-105313, 2019.

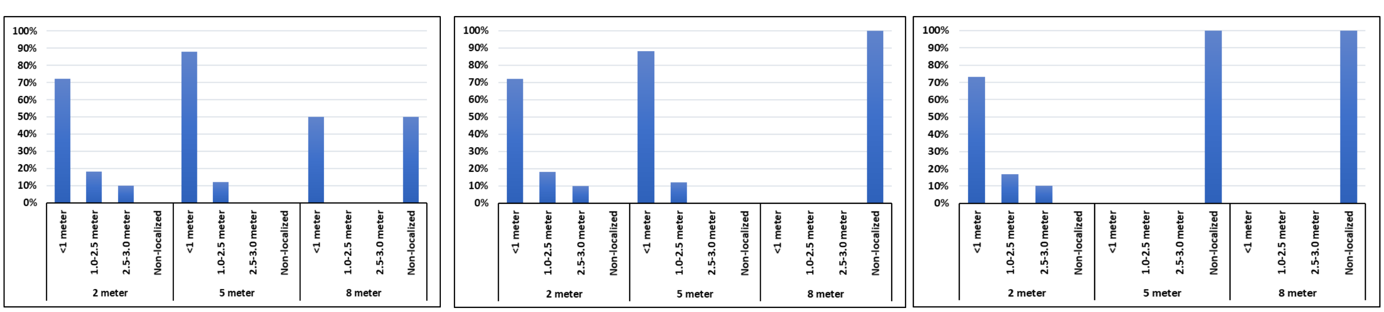
[17] ABMM Rahman, T. Li, Y. Wang, "Recent Advances in Indoor Localization via Visible Lights: A Survey." *Sensors,* 20(5), 1382. 2020.

[18] B Soner, and S Coleri, "Visible Light Communication Based Vehicle Localization for Collision Avoidance and Platooning," *IEEE Trans. on Vehicular Technology*, vol. 70, no. 3, pp. 2167-2180, March 2021.

[19] M. Basappa, R. Acharyya, and G. K. Das, "Unit disk cover problem in 2D," *Journal of Discrete Algorithms*, Vol. 33, pp. 193-201, 2015.

[20] N. Lasla, M. Younis, A. Ouadjaout and N. Badache, "On optimal anchor placement for efficient area-based localization in wireless networks," *Proc. of IEEE Int'l Conf. on Comm. (ICC)*, pp. 3257-3262, 2015.

[21] P. Xie et al., "Aqua-Sim: An NS-2 based simulator for underwater sensor networks," OCEANS 2009, 2009, pp. 1-7



(a) **(b)** **(c)**

Fig. 8. Percentage of node localized vs localization error distance (m) for various depth and (a) 1 picoWatt (b) 1 nanoWatt and (c) 0.1 microWatt minimum sensitivity of optical sensor in Turbid Harbor water.