ABSTRACT In this paper, we studied the probability distribution function (PDF) of the channel gain of dynamic underwater visible light communication (UVLC) model for different types of water using goodness-of-fit (GoF). We used different water channels at different system parameters with dynamic scenarios. First, the Zemax Optics Studio simulator is used to simulate dynamic UVLC channels. UVLC links are examined using Monte Carlo Ray-Tracing (MCRT) simulation for three different water channels; namely, pure sea water channel, clear ocean water channel and coastal ocean water channel at different configuration types. With the presence of blocking divers, we added a dynamic movement in a single input multiple users (SIMU) scenario. Our simulation is based on Zemax Programming Language (ZPL) in sequence with the Zemax Optics Studio. The GoF tests are used to get the degree of fitness between the simulation data and the set of well-known candidate distributions to determine the best fit. We used the R statistical programming language and applied predefined algorithms to determine the optimum degree of fitting for each statistical result. The Kolmogorov-Smirnov (KS), Chi-Square (CS), Cramer-Von-Mises (CVM) and Anderson-Darling (AD) tests are used to represent the four GoF statistical computation techniques for each channel scenario. The received power is enhanced by 35% when the detector movement area increases from 25 m² to 100 m² in clear ocean water channel. The obtained results reveal that the UVLC is best represented by Weibull, Gamma or Lognormal distributions.

INDEX TERMS Goodness-of-fit (GoF), underwater visible light communication (UVLC), Monte Carlo ray-tracing (MCRT), extinction coefficient, statistical distributions.

I. INTRODUCTION
Over the past years, the demands for high-speed underwater communication links are rising due to the development of underwater human applications. This includes environmental monitoring, port protection, tactical surveillance, underwater exploration, offshore oil field exploration, disaster prevention and military operations. On the other hand, there are massive challenges in establishing a traditional underwater wired communication due to implementation costs and lack of flexibility for many underwater applications. This increased the interest in under water wireless communication that transmits data in unguided water environments via wireless carriers [1].

The three major types of underwater wireless communications are radio frequency, acoustic and optical communication. Radio frequency (RF) has a high attenuation in underwater wireless communication. Accordingly, RF is a choice for data rates up to Mbps, particularly in very short distances (less than 10 m). On the contrary to RF, acoustic waves support ranges up to kilometers, but, with limited data rates up to kbps. Additionally, acoustic waves consume power in a range of tens of watts while RF power consumption depends on the distance and differs from milliwatts to hundreds of watts [2].

On the other hand, underwater visible light communication (UVLC) uses light waves as transmission carriers. The optical links power consumption is in range of milliwatts to few watts, depending on the transmitter type; either laser
diodes (LDs) or light emitting diodes (LEDs) and supports high data rates up to Gbps [3]. Moreover, UVLC systems suffer from severe absorption and scattering effects introduced by the underwater channel that needs to be addressed well to mitigate this effect and increases the average link distance which is just a few tens of meters [4], [5].

In a previous work [6] and unlike [2], [7], we performed a dynamic channel modeling considering the presence of man-made objects for the dynamic environment. We used an advanced ray-tracing program Zemax Optics Studio, and LED colors for transmission as well as UVLC. The reflection characteristics of the three types of water which are wavelength dependent. Furthermore, we introduced advanced human Computer Aided Design (CAD) images for realistic channel modeling because the lack of divers and blockage could significantly affect the results.

The underwater light propagation is completely described by the radiative transfer equation (RTE) that can be solved using numerical models [8]. Mobley et al. compared different methods for computing underwater light channels and the obtained results showed that Monte Carlo Ray-Tracing (MCRT) calculations using statistical estimation techniques achieved highly accurate radiance values [9].

C. Shen et al. proposed a 20 m optical wireless link based on 450 nm LDs with a comparatively a high-speed data rate of 1.5 Gbps with tap water [10]. Besides, an experimental study has been performed with a distance of 34.5 m and a data rate of 2.7 Gbps in tap water [11].

In [12], Gabriel et al. proposed a Monte Carlo model for analyzing the effect of distance propagation on underwater optical channel capacity with respect to three types of waters: clean ocean, coastal ocean and harbor waters. It was demonstrated that water quality plays a vital role in channel capacity. The results showed that the channel capacity for clean water, coastal ocean and harbor waters are of the order of hundreds of MHz, tens of MHz and MHz, respectively. This model did not take into account the effect of the aperture size.

A key step towards accomplishing effective and reliable underwater UVLC system design is to recognize the statistical distribution of channel gain via modeling and characterizing the underwater channel. Moreover, the results in [10], [11] motivated us to use reasonable distances (20 and 50 m) in order to evaluate the system performance.

Researchers used goodness-of-fit (GoF) statistics to assess the degree of fitting of statistical distributions, taking into account the sampling variability, the magnitude of the discrepancy between the data and the model to assess the overall GoF of the models [13]. Academicians and researchers used the R programming language for data statistical analysis because it provides all the possible GoF tests [14].

To clarify novelty in this paper, we present a reliable dynamic UVLC channel that exactly defines the absorption and scattering effects with specific link configuration, transmitter and receiver architecture and alignment state. We study the statistical distribution of our UVLC model using GoF techniques by four statistical tests with several well-known distributions. Moreover, we use the predefined algorithms of the R statistical programming language in order to fit the dynamic gain variations with the best statistical distributions, for three different water types in a dynamic environment. We analyzed the probability distribution function (PDF) of our UVLC model under different system parameters with complex scenarios that are applied on pure sea water, clear ocean water and coastal ocean water, respectively. We applied the MCRT method using Zemax Optics Studio and Zemax Programming Language (ZPL) for the underwater dynamic channel simulation of the three mentioned water types. This is considered a reliable practical setup simulator which provides results typical to experimental results.

We propose a practical Single Input Multiple Users (SIMU) model mobility algorithm. Various configurations of aperture size and propagation distance effects on the received signal strength are investigated. We aim getting practical models by applying the dynamic mobility algorithm which causes severe fading in the system compared with assumption of static channel studied by most of researchers in the literature.

There are multiple applications that need underwater wireless optical communication. For example, we can replace the moving divers by remotely operated vehicles (ROV) with Underwater Robotic Assistant (UWRA) that act as a robotic dive buddy.

The remainder of the paper is organized as follows. In Sec. 2, we define briefly the used channel fading conditions of the UVLC channel. Section 3 describes our Monte Carlo simulator Zemax Optics Studio and the dynamic mobility algorithm. In Sec. 4, we demonstrate the GoF tests and the programming language. Numerical results are presented and discussed in Sec. 5. Finally, Sec. 6 is devoted to the main conclusions and some future directions.

II. OPTICAL COMMUNICATION CHANNEL

The wide variability in natural waters optical properties is the motivation for creating precise and easily organized data. In addition, it is great to figure out the relevance between optical properties and natural water biological, chemical and geological elements. The water optical characteristics are expediently divided in two classes which are mutually exclusive: inherent and apparent.

These properties which are only medium dependent are inherent optical properties (IOPs). The predominant IOPs of water are the absorption coefficient, the scattering coefficient and the attenuation coefficient [3].

A. ABSORPTION AND SCATTERING

Absorption and scattering are the two dominant causes of attenuation in the wireless link when light propagates through the body of water [15], [16].

In general, the propagation of light through water is defined by the total extinction coefficient \( C(\lambda) \) which is wavelength dependent. It is a measure of the impact of the absorption and the scattering coefficients, respectively, \( a(\lambda) \) and \( b(\lambda) \).
The total extinction coefficient $C(\lambda)$ is given by [12].

$$C(\lambda) = a(\lambda) + b(\lambda),$$

(1)

$a$ and $b$ represent the absorption and scattering contributions and $\lambda$ is the transmission wavelength.

Absorption is the loss of light energy in mediums when photon energy is transmitted through interaction with water molecules, dissolved colors, organic subjects, phytoplankton and particles. It depends on the fluctuation of the refractive index, $n$, of the medium and the light wavelength, $\lambda$. Scattering is the deflection of light via the interaction with molecules or particles along with its original path [8].

According to a wide variety of scattering and absorption properties in water, they have been classified into various water types that have almost the same optical properties [4]. There are four major types of waters and their structure differ from a region to another. Our study focuses on only three types: pure sea water with a minimum scattering effect, so that, the propagation beam slightly straight and the main contribution factor is only the absorption of molecules, clear ocean water that is affected mainly by the high dissolved particles concentration, and coastal ocean water with much more significant planktonic and mineral components influences absorption and scattering [17].

In most waters, phytoplankton has a significant role to play in determining the optical characteristics of these waters. A chlorophyll and pigments strongly absorb light in the blue and red spectral regions of phytoplankton located near the water surface and the sunlight.

Different values of chlorophyll concentration in each are used to characterize different types of waters. Table 1 indicates the absorption and scattering measured values and the total attenuation in chlorophyll concentration which are used in this paper.

**TABLE 1.** Absorption, scattering and extinction coefficients for water types [12], [16], [18].

<table>
<thead>
<tr>
<th>Type</th>
<th>Chlorophyll concentration</th>
<th>$a(\lambda)$</th>
<th>$b(\lambda)$</th>
<th>$C(\lambda)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure sea water</td>
<td>0.005</td>
<td>0.053</td>
<td>0.003</td>
<td>0.056</td>
</tr>
<tr>
<td>Clear ocean water</td>
<td>0.31</td>
<td>0.069</td>
<td>0.08</td>
<td>0.15</td>
</tr>
<tr>
<td>Coastal ocean water</td>
<td>0.83</td>
<td>0.088</td>
<td>0.216</td>
<td>0.305</td>
</tr>
</tbody>
</table>

**B. COMMUNICATION LINKS**

The line of sight (LoS) communication link is the direct link between the transmitter and the receiver which means that the receiver is in front of the LED field of view (FOV).

The LoS connections are not always possible with realistic systems. They require a very tight framework for pointing and tracking mobile platforms to be kept for both transmitters and receiver bore-sighted. The underwater environment, bubbles and suspended particles increase the risk of beam blockage [3], [18].

The Non-LoS (NLoS) communication link is an indirect optical link which is built on the water-air interface by means of the back-reflection of the propagating optical signal. A further way of using NLoS links is to spread or diffuse the optical light from the LEDs to boost the receiver FOV [18], [19].

**III. DYNAMIC CHANNEL SIMULATION**

The simulation of the dynamic optical wireless channel explores the VLC channel effects of a movable source and receivers with realistic environment scenarios. While the static VLC channel relies on unique scenarios and does not contain all possible channel variance scenarios [20], [21]. We added a blockage in the area between the source and the receiver for realistic simulations. Moreover, the dynamic scenario is intended to determine the source and detector parameters that can withstand dynamic channel changes.

**A. CONCEPT OF THE SIMULATION MODEL**

We study three different water types: pure sea water, clear ocean water and coastal ocean water. For each water type, we simulate the effect of detector area, movement area, source array and link distance between the transmitter and the receiver as shown in Fig. 1.

![FIGURE 1. The configurable parameters for each type of water in the dynamic channel modeling.](image)

The simulation model consists of several modules as shown in Fig. 2. We define the geometry of the underwater environment and add the objects. We specify the reflection coefficient of the objects. We also define water types with their extinction coefficients and the specification of the source and detectors. We develop a uniform random motion algorithm for both source and detectors divers. The UVLC channel modeling in Zemax Optics Studio is used; namely, a non-sequential ray-tracing feature, to calculate the detected power at the receivers. Then, we determine the best fit by GoF analysis using the R programming language.

The channel impulse response, $h(t)$, used in the MCRT solver Zemax Optics Studio is defined by [4], [5]

$$h(t) = \sum_{i=1}^{N_r} P_i \delta(t - \tau_i),$$

(2)

where $p_i$ and $\tau_i$ are the power and delay for the $i$th ray, respectively, and $N_r$ is the total number of rays emitted by the LEDs. Accordingly, the channel DC gain, $H_0$, is defined by [4]

$$H_0 = \int_{-\infty}^{\infty} h(t) \, dt,$$  

(3)

The channel DC gain is considered one of the most important parameters needed in VLC channel modeling. The total
received power at the receiver is defined by [22]

\[ P_r = P_t H_d(0) + \int_{-\infty}^{\infty} P_t H_{ref}(0), \]  

where \( H_d(0) \) and \( H_{ref}(0) \) are the DC channel gain of the direct and reflected paths, respectively, and \( P_t \) is the total optical transmitted power by LEDs. The better channel gain gives the better received power. Accurate channel characterization is an important prerequisite to set the system parameters appropriately.

The effect of the fading caused by the random movement of divers and therefore the orientation of the detector is examined. The coefficient of channel extinction is considered as a wavelength dependent as mentioned before.

As shown in Fig. 3, we use advanced divers CADS with human dimensions 180 cm, 40 cm, and 20 cm, respectively, for height, width, and depth. Also, the existence of blockage divers in the mid distance between the transmitting and receiving divers is applied for a realistic channel modeling.

For pure sea water channel, we used the blue color (460 nm) because it is proven to possess satisfactory performance. For clear ocean water and coastal ocean water channels, we used cyan color (490 nm) to induce the most effective performance. In our previous work [6], we proved that cyan has the best performance, while the blue and green colors come in the 2nd and 3rd orders after cyan. Accordingly, the cyan performance has the lowest absorption and scattering coefficients in ocean water.

**B. SINGLE INPUT MULTIPLE USERS (SIMU) MODEL MOBILITY ALGORITHM**

The SIMU mobility algorithm, is the algorithm where the source diver communicates with 5 moving divers and each encompasses a detector in order that the power is shared between five divers rather than one diver as described in [5], [23]. The distance between the source and receiving divers is set to 23 m and 50 m, where each diver carrying a receiver is 1.5 m apart. The orientation angle is assumed to be fixed, which means that the divers do not rotate around the x axis. The tilt angle is set as a uniform distribution from 0° to 180°. When the tilt angle is chosen randomly to be either 0° or 180°, this means that the diver is parallel to the x axis in positive and negative directions, respectively. As shown in Fig. 3(a), the tilt angles of the source diver and the receiver diver Rx2 are, respectively, 170° and 90°. In Fig. 3(b), the dynamic random motion changes the tilt angles of the source diver and the receiver diver Rx2 to 30° and 25°, respectively.

Furthermore, the divers are not aligned in the same horizontal axis as they can move to any random position in an area...
of 25 m² or 100 m². Accordingly, the source and receivers have variable x and y coordinates in each simulation and are fixed in z the coordinate.

We define the positions for each diver for 400 seconds according to a random motion algorithm. Each second has different positions and orientations for the five divers. Consequently, new channel gain calculations are mandatory for each second which allows us to configure 400 iterations.

The source beam direction is highlighted with green color, and the receiver beam angle is highlighted with the white color, as illustrated in Fig. 3. Also the detector area is set to be 1 cm² and 5 cm². In addition, the source array is set to be 10 × 10 and 16 × 16 LED chips array, the power of each LED chip is 2 W and the number of rays per LED chip in the Zemax Optics Studio simulator is 500,000 rays [4]. Moreover, the depth of the transmitting and receiving divers is 25 m [4], [5].

IV. STATISTICAL GOODNESS-OF-FIT
Data distribution fitting statistics is a popular task and requires the selection of a probability distribution of the data along with providing estimates of the parameters for that distribution [24]. Generally, there are many well-known probability distribution functions used to represent the distribution of a specific application.

The GoF tests are carried out to find the degree of fitness between the experimental data and the well-known distributions to select the best distribution for experimental data.

GoF presents the statistical method used to assess whether or not the Empirical Distribution Function (EDF) that is estimated on the basis of our experimental data can fit for theoretical distribution by comparing the difference between theoretical and empirical PDFs [25]. Accordingly, the lower the potential difference, the closer the model to the actual data, and the PDF of this model is called the “best fit”. The statistical tool R is used to identify the GoF measures. To find the best-fitting distributions by means of a maximum likelihood estimation, the R “fitdistrplus” package is used. The R “fitdistrplus” package permits distinctive estimation procedures. This package combines various functions to find and study the best-fit of preferred distributions of a similar combination of data [26].

In general, it is important to pick the good candidate distributions before fitting one or more distributions to the data set. Descriptive statistics can help in selecting the candidate distributions that could observe the best fit distribution between a set of theoretical distributions [27]. Accordingly, Skewness and Kurtosis is an appropriate plot in this case. Kurtosis is a calculation used to indicate the tail of a distribution. The heavy tail distribution has a Kurtosis value greater than three. The Skewness measures the distribution asymmetry amount on its mean. The Skewness of a distribution has a positive value mean that the part of a probability density function on the right of the mean is “fatter” than the left [13], [25]. Moreover, using the P-P plot, we could graphically observe the degree of best fitting simulated cases. Also, we could get the empirical distributions of the simulation against fitted theoretical distributions functions.

CVM, KS, CS and AD tests are classically considered the common four GoF statistics to fit continuous distributions [25]. They can be obtained using the function “gofstat” which is predefined in R “fitdistrplus” package.

The CS test is generally used to compare the statistical degree of fitness between the measured data and a specific theoretical distribution function [24]. The KS is based on the greater vertical difference between the hypothesized and empirical distributions. The AD is a modified version of the KS version that gives greater weight to the tails than the KS test of a population with a similar distribution [28]. The CVM estimates the minimum distance among theoretical and sample probability distributions. The statistical tool R implements a wide range of GoF tests in order to identify the compatibility of the classical distributions KS, and CS as well as the additional sophisticated algorithms AD and CVM. Therefore, the R-Statistical tool is ideally adapted for the statistical analysis of the different fitness measures.

The R predefined distributions: Weibull, Gamma, Nakagami, Exponential, Normal and Lognormal are used with the predefined functions included in the R fitdistplus package to calculate the GoF using the R predefined KS, CS, CVM, and AD tests.

V. NUMERICAL RESULTS
We configured 16 different scenarios in each water type as listed in Table 2. Figure 4 displays the power received in each case of the three used water types. The results reveal that Case H exhibits the best performance as the receiver collects more rays than other cases in all types of water with a largest detector area of 5 cm² and a maximum divers movement area of 100 m². Also, it uses the maximum source array 16 × 16 through the minimum distance 23 m.

<table>
<thead>
<tr>
<th>Case</th>
<th>Link distance (m)</th>
<th>Source Array (LED chips)</th>
<th>Detector area (cm²)</th>
<th>Movement area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>23</td>
<td>10 × 10</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>B</td>
<td>23</td>
<td>10 × 10</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>C</td>
<td>23</td>
<td>10 × 10</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>D</td>
<td>23</td>
<td>10 × 10</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>E</td>
<td>23</td>
<td>16 × 16</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>F</td>
<td>23</td>
<td>16 × 16</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>G</td>
<td>23</td>
<td>16 × 16</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>H</td>
<td>23</td>
<td>16 × 16</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>I</td>
<td>50</td>
<td>10 × 10</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>J</td>
<td>50</td>
<td>10 × 10</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>K</td>
<td>50</td>
<td>10 × 10</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>L</td>
<td>50</td>
<td>10 × 10</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>M</td>
<td>50</td>
<td>16 × 16</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>N</td>
<td>50</td>
<td>16 × 16</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>O</td>
<td>50</td>
<td>16 × 16</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>P</td>
<td>50</td>
<td>16 × 16</td>
<td>5</td>
<td>100</td>
</tr>
</tbody>
</table>

TABLE 2. List the 16 water dynamic scenarios.
Moreover, the GoF tests for MCRT simulation outputs are calculated in each water type. Consequently, a total of 48 GoF tests were calculated using KS, CS, CVM, and AD tests in each water type.

It is obvious that the received power with a large link distance 50 m suffers great degradation for all types of water, as shown in Fig. 4. However, we managed to solve that decay in cases O and P for pure sea water by using a detector area of 5 cm$^2$ and source array of 16 $\times$ 16. Assuming that the minimum threshold of receiver is in the microwatt range, no link failure will occur with the link distance of 50 m and a detector area of 1 cm$^2$ with a source array of 10 $\times$ 10.

A. PURE SEA WATER CHANNEL

We obtained the received power for the 16 construction cases as illustrated in Table 2. Then, we obtained the GoF to figure out the best fit distribution of each case.

In the calculation of the best fitting distribution of Case A, we used the Skewness-Kurtosis plot to pick the candidate distributions. The calculated value of Skewness is positive and Kurtosis value is larger than 3 which means that the distribution has a long right tail. As shown in Fig. 5, the observation point is the position of the estimated Kurtosis and square of Skewness that best fits the data. As long as the distribution is near the observation point, this means that the candidate can provide best presentation of data. The observation point with the blue circle notation is close to Weibull, Gamma, Lognormal and Exponential distributions. As per the definition of Skewness-Kurtosis, the closer the distance to the distribution the more probability for the distribution to best fit the data.

Figure 6 shows the data histogram with selected theoretical fitted PDFs and Fig. 7 shows the P-P plot that indicates high probability for Gamma and Weibull distributions to best fit the data distributions.

The GoF values for Weibull, Gamma, Lognormal, Normal, Nakagami and Exponential distributions are calculated and illustrated in Table 3 which also includes all the distributions parameters. We present only the GoF tests of cases A and P indicating the best fit distributions that have the best GoF value. As for KS, CVM, AD tests, the lower the GoF value the better the distribution that fits data. Unlike the other tests, CS is chosen by selecting the highest GoF value to indicate the best distribution. It is noticeable that either the Weibull or the Gamma distributions are the best fit. Additionally, the same procedures are followed for all other remaining pure sea water cases, and the obtained results disclosed that the best fits are either Weibull, Gamma or Lognormal distributions.
TABLE 3. List of the GoF values of pure sea water: cases A and P.

<table>
<thead>
<tr>
<th>GoF Test</th>
<th>Case</th>
<th>Exponential (rate)</th>
<th>Lognormal (meanlog, sddllog)</th>
<th>Weibull (shape, scale)</th>
<th>Normal (mean, sd)</th>
<th>Gamma (shape, rate)</th>
<th>Nakagami (shape)</th>
<th>Best Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>KS</td>
<td>A</td>
<td>$4.016 \times 10^{-2}$</td>
<td>$9.25 \times 10^{-2}$</td>
<td>$6.2 \times 10^{-2}$</td>
<td>$28.88 \times 10^{-2}$</td>
<td>$10.47 \times 10^{-2}$</td>
<td>$50.81 \times 10^{-2}$</td>
<td>Weibull</td>
</tr>
<tr>
<td>CS</td>
<td>A</td>
<td>$0$</td>
<td>$9.45 \times 10^{-12}$</td>
<td>$5.79 \times 10^{-2}$</td>
<td>$0$</td>
<td>$3.59 \times 10^{-11}$</td>
<td>$0$</td>
<td>Weibull</td>
</tr>
<tr>
<td>CVM</td>
<td>A</td>
<td>$15.76$</td>
<td>$64.54 \times 10^{-2}$</td>
<td>$35.98 \times 10^{-2}$</td>
<td>$83.19 \times 10^{-1}$</td>
<td>$50.64 \times 10^{-2}$</td>
<td>$21.79$</td>
<td>Weibull</td>
</tr>
<tr>
<td>AD</td>
<td>A</td>
<td>$16.42 \times 10^1$</td>
<td>$48.8 \times 10^{-1}$</td>
<td>$22.83 \times 10^{-1}$</td>
<td>$42.59$</td>
<td>$26.53 \times 10^{-1}$</td>
<td>$101.68$</td>
<td>Weibull</td>
</tr>
<tr>
<td>Parameters</td>
<td>A</td>
<td>$60.81 \times 10^3$</td>
<td>$-13.34$</td>
<td>$42.61 \times 10^{-2}$</td>
<td>$1.64 \times 10^{-4}$</td>
<td>$29.72 \times 10^{-2}$</td>
<td>$18.07 \times 10^3$</td>
<td>$3.51 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

TABLE 4. List of the GoF values of Clear ocean water: cases C and H.

<table>
<thead>
<tr>
<th>GoF Test</th>
<th>Case</th>
<th>Exponential (rate)</th>
<th>Lognormal (meanlog, sddllog)</th>
<th>Weibull (shape, scale)</th>
<th>Normal (mean, sd)</th>
<th>Gamma (shape, rate)</th>
<th>Nakagami (shape)</th>
<th>Best Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>KS</td>
<td>C</td>
<td>$47.61 \times 10^{-2}$</td>
<td>$10.28 \times 10^{-2}$</td>
<td>$10.42 \times 10^{-2}$</td>
<td>$32.89 \times 10^{-2}$</td>
<td>$11.75 \times 10^{-2}$</td>
<td>$45.29 \times 10^{-2}$</td>
<td>Lognormal</td>
</tr>
<tr>
<td>CS</td>
<td>C</td>
<td>$2.18 \times 10^{-1}$</td>
<td>$1.49 \times 10^{-2}$</td>
<td>$6.08 \times 10^{-2}$</td>
<td>$5.25 \times 10^{-48}$</td>
<td>$5.18 \times 10^{-4}$</td>
<td>$0$</td>
<td>Weibull</td>
</tr>
<tr>
<td>CVM</td>
<td>C</td>
<td>$35.2 \times 10^{-2}$</td>
<td>$55.58 \times 10^{-2}$</td>
<td>$7.82 \times 10^{-2}$</td>
<td>$3.68$</td>
<td>$10.28 \times 10^{-2}$</td>
<td>$26.92 \times 10^{-2}$</td>
<td>Weibull</td>
</tr>
<tr>
<td>AD</td>
<td>C</td>
<td>$2$</td>
<td>$3.66$</td>
<td>$47.28 \times 10^{-2}$</td>
<td>$20.43$</td>
<td>$57.52 \times 10^{-2}$</td>
<td>$123.58$</td>
<td>Weibull</td>
</tr>
<tr>
<td>Parameters</td>
<td>C</td>
<td>$8.28 \times 10^3$</td>
<td>$-9.7$</td>
<td>$90.74 \times 10^{-2}$</td>
<td>$12.08 \times 10^{-3}$</td>
<td>$85.98 \times 10^{-2}$</td>
<td>$7.12 \times 10^{-2}$</td>
<td>$47.73 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

All the percentage increase of the received power for all cases are compared relative to Case A. Accordingly, Case A is denoted with 0% percent increase as it is the reference power. In comparison with case A, the received power was increased by 89.4, 49.2 times in cases H and G, respectively, as shown in Fig. 8. Furthermore, with using the longest distance 50 m the received power enlarged by 4.5, 6.3 times in cases O, P, respectively, with respect to case A.

The received power was declined by practically 86% with the distance increase to 50 m. On the contrary the detector area improved the received power by nearly 2600%. Besides, the 16 × 16 source array enhanced the power by 134%. In addition, the movement increase to 100 m enhances the received power by almost 32%.

B. CLEAR OCEAN WATER CHANNEL

Repeating the previously mentioned steps to analyze the channel gain of 16 clear ocean water channel cases. For case A, the Skewness-Kurtosis calculation unveils that the data may be fitted well by Weibull, Gamma or Lognormal. Furthermore, the calculated value of Skewness is positive, and the Kurtosis equals 19.23. Therefore, the received power is fitted with selected Weibull, Gamma,
and Lognormal as well as Exponential, Nakagami and Normal distributions. The P-P graph in Fig. 9 shows that Weibull and Lognormal distributions are the best fitting distributions.

The values of GoF are calculated in Table 4 for cases C and H. The results reveal that Lognormal or Gamma distributions are the best fit distributions with the lowest GoF value. In all other cases, the best fits are either Weibull or Gamma or Lognormal distribution.

The received power is faded by almost 99% with a link distance of 50 m. As shown in Fig. 4, the power decreases dramatically due to the large distance 50 m despite using the greatest detector area of 5 cm$^2$ and strongest source array of 16 $\times$ 16 in cases O and P.

Moreover, the received power of clear ocean water for cases A and H is 3.61 mW, 318.96 mW, respectively. The received power is enhanced by 8731%, 5426% in cases H and G, respectively, with respect to case A, as shown in Fig. 10. The received power is enlarged by 127% with using the 16 $\times$ 16 source array. Also, the 5 cm$^2$ detector area enhances the received power by 2100%. Additionally, the movement area 100 m$^2$ improves the received power by 35%.

C. COASTAL OCEAN WATER CHANNEL

The Skewness-Kurtosis calculation of case A shows that the data may be fitted well by Weibull, Gamma or Lognormal, where the calculated value of Skewness is positive, and the Kurtosis value equals 19.9.

Therefore, we select the Weibull, Gamma or Lognormal distributions, besides Exponential, Nakagami and Normal distributions. The P-P graph in Fig. 11 shows that the Gamma distribution can better fit the data than other distributions.

The received power with a link distance 50 m is faded by almost 100%. Also, with using the largest detector 5 cm$^2$ and the strongest source array 16 $\times$ 16, the received power decayed by 100%, as shown in Fig. 4. Moreover, the power is doubled 56.7 times in case H with respect to case A, as shown in Fig. 12.

The source array 16 $\times$ 16 enhances the received power by almost 124%. Furthermore, the movement area 100 m$^2$ increases the received power by 37%. The major impact is due to the detector area increase to 5 cm$^2$, that increases the received power by 1700%.

Furthermore, the channel gain in 16 Coastal ocean water scenarios is analyzed using the GoF criteria. The obtained values of GoF are shown in Table 5 for cases B and G.
The results disclose that Gamma distribution is the best fitting distribution as it exhibits the lowest GoF value. On the other hand, the Weibull, Gamma, Lognormal distributions are the best distributions for the rest of cases.

VI. CONCLUSION

In this paper, we provide a comprehensive study for dynamic channel modeling inside different types of water using the sources colors that provide minimum extinction coefficient in UVLC. In addition, the UVLC channel was simulated using extensive practical MCRT simulator setup by the Zemax Optics Studio combined with ZPL in order to enable dynamic random mobility algorithm. Moreover, a blocking environment of divers has been carried out in three channel links: pure water, clear ocean water and coastal ocean water in order to examine the distribution of the channel gain variations under different source and receiver specifications.

Furthermore, we examined the GoF using CVM, KS, CS and AD tests to identify the best fit distributions for the channel gain. The results reveal that Weibull, Gamma and Lognormal distributions give the best fitting for the channel gain in different scenarios while the Exponential and Nakagami distributions do not fit in any case.

On the other hand, the obtained results reflect the effect of changing the UVLC transmitter and receiver parameters. We found that increasing the detector area from 1 cm$^2$ to 5 cm$^2$ enhances the received power at least 1700%. The received power is enhanced by maximum 134% with increasing the source array from 10 × 10 to 16 × 16. In addition, the power received is increased by almost 32% when the detector movement increases from 25 m$^2$ to 100 m$^2$. The contrary, increasing the link distance from 23 m to 50 m leads to the degradation of the received power.

The results give better comprehension of the UVLC channel and a reasonable design of an UVLC system. The resulted distributions due to dynamic channel gain variations enable the system designers to quantify the effects of user mobility.

This is beneficial in designing handover, channel assignment algorithm, and proper design for transmitter and receiver specifications.

REFERENCES

M. Mahmoud et al.: Statistical Studies Using GoF Techniques With Dynamic UVLC Channel Modeling


