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Research Article

Impact of Marine Environment and Seawater Bubbles on Underwater RF Communications at 1 MHz, 100 MHz, and 1 GHz

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Abstract: The underwater area is increasingly important for getting resources, understanding ecology, and maintaining national safety. Communication between underwater vehicles and flying platforms is key to achieving these goals. But the marine environment, with factors such as salinity, conductivity, and roughness, coupled with bubbles from wind, living things, and human stuff, strongly affects how radio frequency (RF) signals travel. These bubbles change how seawater works for signals, causing them to lose strength, scatter around, or bend, which makes it harder for underwater-to-air communication systems to work well. This paper looks at how bubbles affect RF communication with Monte Carlo simulations, looking into bubble size groups, the count of bubbles, and environmental issues such as water depth and wind speed. The study also quantifies scattering and absorption losses caused by bubbles, while proposing mitigation strategies to address these impairments. The results show difficulties along with possible answers for making RF communication better in bubbly sea areas, stressing that using flexible methods can help make signal trustworthiness better.

***Keywords*:** underwater-to-air communication, marine environment, seawater bubbles, RF signal propagation, Monte Carlo simulations

1. Background and introduction

Underwater search operations have gained significant importance in recent years. This is because we want to find natural things, know more about sea life changes, and maintain the security of the country. Humans only live on 29% of Earth's land, most of which is under water, making underwater searching crucial. To help with these marine projects, the technology for talking and sharing information is very needed. To know how talk happens between underwater and above the air, we must study the things in nature that change how signals move. This matters more now since there is more need for RF communication underwater, like in ocean studies and military uses. One big thing affecting RF signals is bubbles in seawater because they have special traits. Bubbles change how seawater handles electrical properties, which makes signals weaken or bend differently. These small areas caused by bubbles create big problems for talking systems underwater. Scientists want to learn about these issues and see what impact they have on RF communication success by mixing ideas from sound engineering and electromagnetic science.

Seawater presents significant challenges for radio wave propagation due to high conductivity and variable permittivity, leading to rapid attenuation, especially at higher frequencies, although extremely low-frequency (ELF)

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bands can travel long distances with low attenuation, they require large antennas and high power [1]. Physically realistic models have been developed to better understand the variation of seawater's dielectric constant with frequency and salinity [2]. However, the ubiquitous presence of bubbles, whether naturally occurring or artificially introduced, further complicates transmission by creating a two-phase medium that modifies the electromagnetic properties of seawater, affecting signal attenuation and speed. Field experiments have characterized bubble clouds, measuring parameters like sound speed, void fraction (e.g., 0.001%), and bubble number density (e.g., 2×10^6 bubbles/m^3) which vary significantly with depth and environmental conditions [3]. The mechanisms by which bubbles affect radio waves include altering the effective permittivity and conductivity of the medium, scattering electromagnetic energy away from the propagation path leading to attenuation and fading, similar to effects observed for optical waves [4], and potentially causing resonance effects and significant propagation delays, mirroring characteristics seen in acoustic wave propagation through two-phase foams [5]. The impact of bubbles is frequency-dependent; lower frequencies generally experience less attenuation, but interactions involving scattering and resonance become pronounced when bubble size is comparable to the wavelength [6]. This frequency dependence also influences the reduction in wavelength observed in seawater, which can enable antenna miniaturization but must be balanced against increased attenuation [6]. Experimental studies, such as those using high frequency (HF) channel testbeds, have investigated propagation losses in controlled bubbly environments, sometimes finding decreased losses compared to theory under specific conditions [7], although laboratory measurements face challenges like mitigating reflections from tank walls [8]. Recognizing the difficulties of through-water transmission, particularly in bubbly regions, research has explored alternative paths like surface electromagnetic waves propagating along seawater-air and seawater-seafloor interfaces, demonstrating potential for carrying broadband signals over practical distances [9], and seabed propagation models utilizing evanescent waves, which theoretically offer significantly lower loss and higher propagation speeds compared to direct line-of-sight paths in seawater [10].

Underwater-to-air communication, sometimes called air-water (A-W) wireless communication, is getting more attention because of its use in exploring oceans, checking the environment, and military work [11]. A-W communication types are indirect link, direct RF link, light-based link, magnetic induction link, and sound-based or acoustic link.

- Indirect link: This method uses a surface point as a go-between for underwater and air nodes. It can use special tech made for both areas but needs more tools and has longer delays due to multi-step (multi-hop) connections [11].

- Direct RF link: Direct RF link is good for fast carrier speed and no bother from noise, but it loses strength a lot and can't go far in water [12].

- Light link: Light link gives much bandwidth but needs a clear view; line-of-sight and dirty water make it hard [12]. Light link looked more for use underwater to air stuff, with ideas like mixing electromagnetic tracking with light systems to make it better [13].

- Magnet induction (MI) link: MI gives secret features and steady channel response, but it can only go short distances and works based on how devices are turned [12], [13]. The steadiness of MI link has been a big research point, especially about how sending devices turn in different underwater places [14].

- Sound link: acoustic waves can do long-distance chatting but have slow data speeds and delays, and get affected by background noise [12], [14]. Acoustic link has also been looked at as a good choice for underwater communication, since it works well for long distances, but there are problems with background noise and how it affects sea animal noise [15]-[17].

One main issue is seawater bubbles that change how electricity behaves in water, which makes RF signals weaker and scatter more [11], [17], [18]. These bubbles can distort RF signals, causing bigger losses of signal strength and chances of bad quality signals. They also bring extra trouble like phase changes and multiple paths that can increase mistakes in data. Many research papers have studied bubble creation and its effects on RF travel, mainly looking at the size and amount of bubbles made by breaking waves [18]-[20]. Bubbles in seawater can take in RF energy, making signals weaker. How much they absorb depends on things like how big the bubbles are, what frequency the RF signal has, and how many bubbles there are.

Research by Rossing [21] shows that absorption goes up with higher frequencies, especially for bubbles that match sizes to RF wavelengths. When bubbles are present, it messes with the medium's refractive index, which leads to reflection and bending of RF signals. This can make multipath propagation happen and distort signals more, complicating communication even further. The study done by Preisig [22] helps understand acoustic behavior influenced by bubbles too and offers a way to think about how RF reflects and bends underwater. For bubbles similar in size to the RF wavelength, Mie scattering is key here as this type affects signal loss greatly while also changing how signals move, thus impacting the received strength and quality of those signals too [23]-[27]. The effects of Mie scattering in environments with many bubbles have been looked at, especially how these bubbles affect electromagnetic waves both in controlled settings and natural bubble distributions [28], [29]. Smaller bubbles compared to the RF wavelength cause Rayleigh scattering. This is not as strong as Mie scattering, but many small bubbles can still noticeably weaken signals [30]-[33]. Research on smaller bubbles has been done using lab tests and computer models, showing they play a part in weakening signals overall [29], [33].

This study uses Monte Carlo simulations for looking at how RF signals and seawater bubbles interact. By including bubble size, density, and factors like wind speed and depth, the aim is to measure how bubbles affect RF propagation. The findings are meant to help create better communication strategies and system designs that deal with the problems caused by bubbles, making underwater-to-air connections more reliable. This study helps to understand the effects of seawater on the transmission of radio waves transmitted through it and then diagnose the attenuation caused by bubbles specifically in seawater on electromagnetic waves.

2. Methodology

The study employs Monte Carlo simulations to model the impact of bubbles on RF signal propagation. The simulations take into account the bubble size distribution, density, and environmental factors such as wind speed and water depth. The simulation framework incorporates models for scattering and absorption coefficients to determine the total path loss due to bubbles.

2.1 *Bubble formation and characteristics*

Bubbles in the ocean come from many things, like waves, living organisms, and human activities. How big they are and how dense they are matter for how they behave with RF signals [17]. There are models called Mie and Rayleigh scattering that help explain this behavior across bubbles of different sizes. Researchers have used photos and sound tools to study bubble traits, which gives more information on how these bubbles interact with RF signals [28], [31], [33]. The way bubbles are sized can be explained using formulas from something called the Hall-Novarini model, which looks at wind speed and depth. The variety of bubble sizes depends on a few things: wind speed, a certain length scale, and a reference size, which changes as depth increases [34]-[38]. This model aids in understanding how bubbles between 10 to 150 μm change in number based on environmental shifts. The size spread is represented by the formulas:

$$n(r,\ z) = \left(1.6\times10^{4}\right)G(r,\ z)\left(\frac{v_{10}}{13}\right)^{3}\exp\left[-\frac{z}{L\left(v_{10}\right)}\right] \tag{1}$$

$$L(v) = \begin{cases} 0.4,\ v_{10}\le 7.5 \\ 0.4+0.115\left(v_{10}-7.5\right),\ v_{10}>7.5 \end{cases} \tag{2}$$

$$G(r,\ z) = \begin{cases} \left[r_{\mathrm{ref}}(z)/r\right]^{4},\ r_{\min}\le r\le r_{\mathrm{ref}}(z) \\ \left[r_{\mathrm{ref}}(z)/r\right]^{4.37+(z/2.55)^{2}},\ r_{\mathrm{ref}}(z)< r\le r_{\max} \end{cases} \tag{3}$$

where $n(r, z)$ is the bubble size distribution as a function of radius r and depth z, $G(r, z)$ represents the bubble distribution influenced by environmental conditions, is the wind speed measured at a height of 10 meters, and $L(v)$ is the characteristic length scale dependent on, indicating the rate at which bubble density decreases with depth. The minimum and maximum bubble radii are set to 10 μm and 150 μm, respectively. Additionally, the reference radius that varies with depth z is defined as [38]:

$$r_{\text{ref}}(z) = 54.4\ \mu\text{m} + 1.984 \times 10^{-6} z \tag{4}$$

2.2 *The bubble number density N(z) (m^-3) and the mean bubble number density $\overline{N}$*

The hall-novarini (HN) model thinks bubbles in ocean water start at 10 micrometers (μm) and leaves out tiny bubbles. The study finds that bubble count changes with depth and wind speed, saying that with a wind speed of 16.5 m/s, max bubble density can hit around 100 million bubbles per cubic meter, which fits well for ocean settings. To look at how bubbles are spread out, the researchers divided the water from top to 8 meters down into eight equal sections or layers, helping them figure average bubble counts in each section [38].

The bubble number density $N(z)$ as a function of depth is calculated by integrating the size distribution over the bubble radii:

$$N(z) = \int_{r_{\min}}^{r_{\max}} n(r, z)dr = \left(1.6 \times 10^4\right) \frac{r_{\text{ref}}^4}{3r_{\min}^3} \left(\frac{v_{10}}{13}\right)^3 \exp\left[-\frac{z}{L(v_{10})}\right] \tag{5}$$

To analyze the bubble distribution, the researchers divide the water from the surface down to 8 meters deep into eight equal layers, making it easier to calculate the average number of bubbles in each layer [38]. The mean bubble number density $\overline{N}_i$ in each layer is calculated as:

$$\overline{N}_i = \int_{z_{it}}^{z_{2i}} N(z)dz / \left(z_{2i} - z_{1i}\right),\ i = 1 \sim 8 \tag{6}$$

where z_{1i} and z_{2i} denote the upper and lower bound of layer i, respectively.

2.3 *Monte Carlo simulation for sea water bubbles generation and their size distribution*

The Monte Carlo simulation simulates the bubble number density distribution in seawater for various wind speeds, depths, and bubble radii. The simulation parameters contain wind speeds ranging from 6 to 16.5 m/s, depths ranging from 0 to 8 meters, and bubble radii ranging from 10 to 150 μm [38]. The simulation uses a 3D array to represent bubble number density as a function of depth, radius, and wind speed, capturing the effects of different environmental conditions on bubble dynamics. The simulation calculates the bubble number density all using the equations above.

2.4 *Monte Carlo simulation of electromagnetic wave propagation and absorption losses in seawater at 2.4 GHz*

This Monte Carlo simulation tests and looks at how electromagnetic waves move through seawater, paying attention to things like losing signal strength, wave speed, and how much energy is lost. The study takes into account environmental aspects like how well the seawater conducts electricity, its ability to store electric fields, and how far signals travel. It's done at 2.4 GHz frequency, mainly trying to figure out how seawater characteristics affect signal movement. To find the path loss, we use a model that relates loss to distance described by an equation [39]:

$$\text{RSS} = 10 \times n \times \log10(d) + C \tag{7}$$

Where n = 3.4 is the path loss exponent for underwater conditions, C = 30 dB is the system loss constant, and d represents the transmission distance, which varies from 0.1 m to 0.5 m. The path loss increases as the distance increases, ranging from -5 dB at 0.1 meters to around 20 dB at 0.5 meters, as shown in Figure 1. This highlights the significant attenuation of electromagnetic (EM) waves over distance in underwater environments. The velocity of EM waves in seawater is computed using the equation [39]:

$$v = \frac{c}{\sqrt{\epsilon_T \cdot \mu_r \cdot \left(1 + \sqrt{1 + \left(\frac{\delta}{\omega \epsilon_r}\right)^2}\right)}} \tag{8}$$

Where $c = 3 \times 10^{-8}$ m/s is the speed of light in vacuum, $\epsilon_r = 81$ is the relative permittivity of seawater, ϵ_T is the total or effective relative permittivity, $\mu_r = 1$ is the typical dimensionless relative permeability of the seawater, $w = 2\pi f$ is the angular frequency in (rad/s) and δ is the seawater conductivity. The wave velocity remains almost constant at approximately 2.357×10^7 m/s across a range of conductivities (0 to 4 S/m). This suggests that conductivity has a minimal effect on wave velocity at the frequency of 2.4 GHz, though it does influence attenuation mechanisms such as absorption [39].

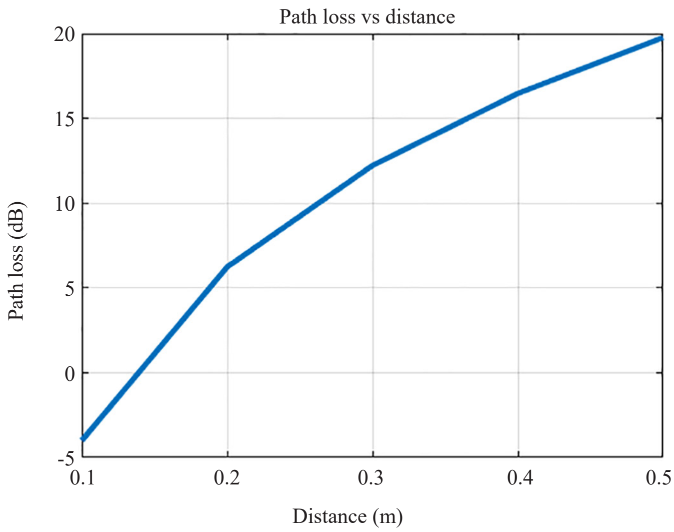

Figure 1. Path loss analysis

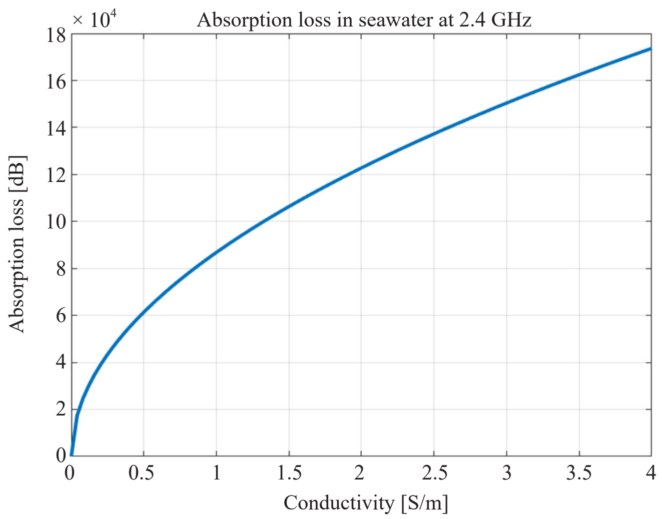

Figure 2. Absorption loss with conductivity

The absorption loss in seawater is modeled by the equation [39]:

$$\alpha = \sqrt{\pi \mu_r f \sigma} \tag{9}$$

Where f = 2.4 GHz, μ_r = 1 is the typical dimensionless relative permeability of the seawater, and σ is the seawater conductivity. The absorption loss increases as conductivity rises, following a nonlinear relationship. At low conductivities, the absorption loss is minimal, but it reaches approximately 1.75 dB at the maximum conductivity value of 4 S/m as shown in Figure 2. This indicates that higher conductivity in seawater significantly increases the attenuation of EM waves, contributing to higher absorption losses.

2.5 *Monte Carlo simulation of RF signal propagation in seawater with bubble-induced scattering and absorption effects*

This simulation search for the effects of seawater and bubbles on the propagation of RF signals by testing electromagnetic (EM) waves traveling through seawater, have frequencies of 1 MHz, 100 MHz, and 1 GHz. Key factors such as conductivity, permittivity, and scattering effects are taken to analyze how these factors influence signal attenuation and scattering. The speed of light in vacuum is $c = 3 \times 10^8$ m/s. The frequency f of the RF signals is swept across the range (1×10^6, 1×10^8, 1×10^9) Hz, with the angular frequency defined by $\omega = 2\pi f$. The wavelength λ of the RF signal in vacuum is calculated using $\lambda = c/f$, vacuum permittivity $\epsilon_\circ$ is a constant valued at $8.854187817 \times 10^{-12}$ F/m, and vacuum permeability μ_0 is set to $4\pi \times 10^{-7}$ H/m. Seawater conductivity σ_{sea} is taken as 4 S/m, and the relative permittivity of seawater ϵ_r is 80, leading to $\epsilon_{\text{water}} = \epsilon_\circ \times \epsilon_r$ [39].

The effective permittivity ϵ_{eff} is variable and calculated using the Maxwell-Garnett mixing theory as [40]:

$$\epsilon_{\text{eff}} = \epsilon \left(\frac{\epsilon + 2\epsilon_{\text{air}} + 2\text{f}\left(\epsilon_{\text{air}} - \epsilon\right)}{\epsilon + 2\epsilon_{\text{air}} - \text{f}(\epsilon_{\text{air}} - \epsilon)} \right) \tag{10}$$

where f is the volume fraction of bubbles. The effective conductivity σ_{eff} is determined by the formula [40]:

$$\sigma_{\text{eff}} = \sigma \times (1 - f) \tag{11}$$

It reflects the reduction in conductivity due to the presence of non-conductive bubbles. The spatial resolution for the FDTD grid is set to the minimum wavelength divided by 20 (min (λ)/20 meters) to ensure stability and accuracy. Bubble concentration N varies with depth according to the exponential decay model [41]:

$$N(z) = N_0 \exp\left(-\frac{z}{\text{scale depth}} \right) \tag{12}$$

Where the initial surface bubble concentration N_0 is 1×10^8 bubbles / m^3 and the scale depth is 10 meters. The volume fraction of bubbles f is derived from the bubble concentration using by the formula [41], [42]:

$$f = N \times \frac{4}{3}\pi r^3 \tag{13}$$

The scattering factor, based on bubble concentration and size, is given by [43]:

$$\text{scattring factor} = 1 + N \times \frac{\left(\frac{2\pi r}{\lambda}\right)^2}{(\epsilon_{\text{eff}} \times \lambda)} \tag{14}$$

Electric and magnetic field update coefficients are calculated to facilitate the FDTD method: the electric field update coefficient mE_x [44] is :

$$mE_x = \frac{\epsilon_{\text{eff}} - \frac{\sigma_{\text{eff}} dt}{2}}{\epsilon_{\text{eff}} + \frac{\sigma_{\text{eff}} dt}{2}} \tag{15}$$

and the magnetic field update coefficient mH_y based on time step and permeability [44], [45] is:

$$mH_y = \frac{dt}{\mu} \tag{16}$$

Where μ is the magnetic permeability (in H/m). The coefficients important for change of electric field E_x and magnetic field H_y in the simulation help to keep model right of EM wave movement through seawater with different bubble amounts. FDTD means Finite-Difference Time-Domain. It is a way used for calculating Maxwell's equations about electromagnetic wave travel and its effect on materials both over time and space. This method is commonly employed in areas like design of antennas, optics, and analysis of electromagnetic compatibility (EMC).

3. Results and discussion

3.1 *Monte Carlo simulation for sea water bubbles generation and their size distribution*

The wind speed spread for the simulation goes from 6 m/s to 16 m/s. It covers this range pretty evenly. Figure 3 shows this distribution. The variety in wind speeds gives a good way to evaluate bubble making with different winds. More moderate wind speeds are shown often, which means the model reflects real-life conditions that impact how bubbles form.

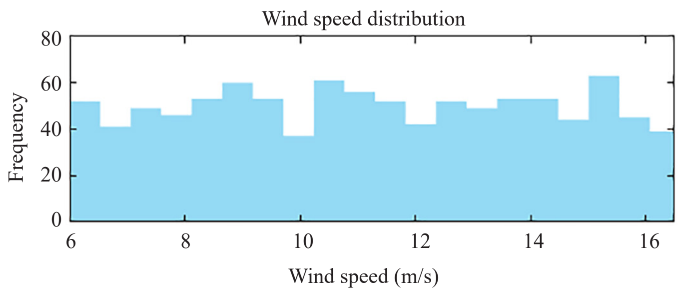

Figure 3. Wind speed distribution

Figure 4 shows the positions of the bubbles at different depths. This figure backs up that indicating a lot of bubbles close to the top and fewer as depth increases. This bubble location is important for RF signals because it means there's more interference from bubbles in shallow water.

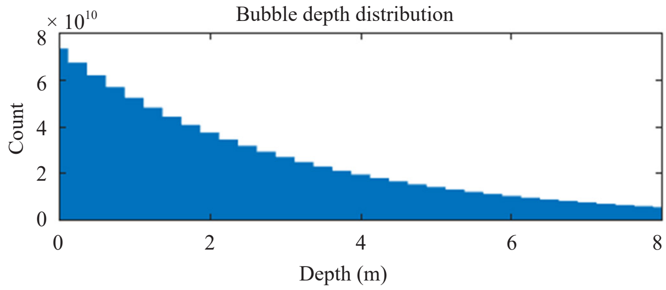

Figure 4. Bubble depth distribution

Bubble radius spread shows lots of little bubbles, seen in Figure 5. The chart tells us that small bubbles under 20 μm occur more frequently, and there is a big decrease for the bigger ones. This pattern hints that conditions around help make small stable bubbles, as shown in Figure 5. These smaller bubbles scatter differently than larger ones and might change how RF signals behave too.

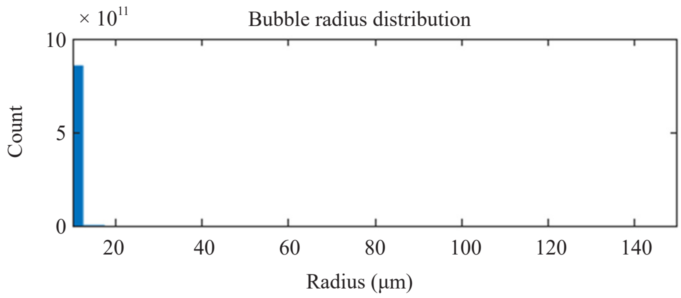

Figure 5. Histogram of bubble radius distribution, indicating a concentration of smaller bubbles under 20 μm

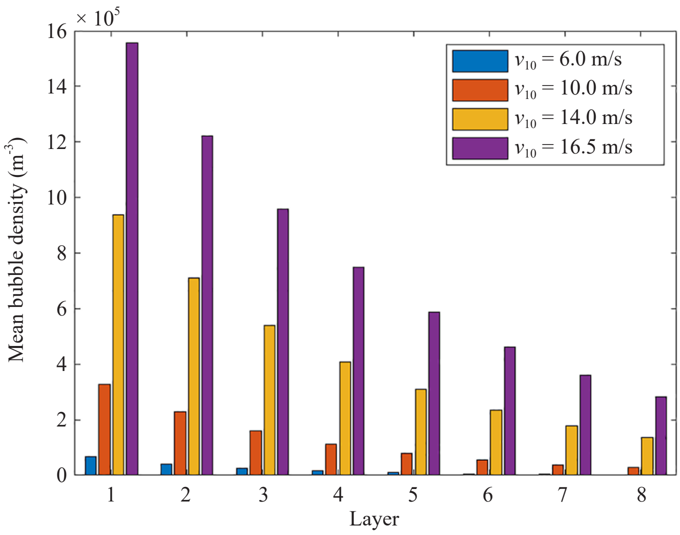

Figure 6. Mean bubble density in each layer

Faster winds make more bubbles in each layer, as shown in Figure 6. This happens since strong winds cause more surface turbulence, making lots of bubbles. The link between wind speed and bubble density distribution matters for underwater radio frequency (RF) signals because more bubbles can scatter and weaken the signal.

3.2 *Monte Carlo simulation of electromagnetic wave propagation and absorption losses in seawater at 2.4 GHz*

The results from the Monte Carlo simulation show a strong link between path loss and distance in seawater at a frequency of 2.4 GHz. Figure 1 indicates that the Path Loss drop goes up in a non-straight way with distance, showing a log-like pattern. Path loss starts at about -5 dB at a small distance of 0.1 m to reach around 20 dB at a bigger distance of 0.5 m, pointing to major signal weakening over short distances. This fast signal loss is due to the high conductivity and dielectric traits of seawater at this frequency. The curve's non-linear style shows that the attenuation gets worse when distances are shorter before it levels off as distances become longer. This fits with expectations in theory since electromagnetic waves lose strength exponentially in conductive materials like seawater.

Absorption Loss Analysis: Figure 2 shows how absorption loss in seawater changes at 2.4 GHz with conductivity levels. The results show increasing in absorption loss with increasing conductivity, following a non-linear relationship. Key observations include:

1. The absorption loss increases from 0 dB at zero conductivity to approximately 1.75 dB at 4 S/m.
2. The increase in absorption loss happens faster at lower conductivity (between 0 and 1 S/m) but slows down as conductivity gets higher.
3. The non-linear behavior suggests a saturation effect in the absorption mechanism at higher conductivity values.

Underwater Communications Implications: The results from these simulations show several key points for underwater wireless communication systems that work at 2.4 GHz.

1. Range Limits: The big path loss (20 dB over 0.5 m) means the communication range is very small, needing either high-power sending or shorter distances between nodes.
2. Signal Processing Needs: The clear pattern of velocity propagation suggests coherent detection methods can be used well, but they must deal with high absorption losses.
3. Design Factors: The strong link between absorption loss and conductivity means adaptive power control might be needed for best performance in different seawater conditions.

3.3 *Monte Carlo simulation of RF signal propagation in seawater with bubble-induced scattering and absorption effects*

This simulation demonstrates that both seawater properties and the presence of bubbles substantially deteriorate RF signal propagation-an effect that becomes increasingly pronounced at higher frequencies. The finite-difference time-domain (FDTD) method was used to model electromagnetic wave behavior over time and space in a seawater environment with and without bubbles. Figures 7, 8, and 9 illustrate the decay of the electric field (E_x) as it penetrates seawater for RF signals at 1 MHz, 100 MHz, and 1,000 MHz . The findings reveal that as the frequency increases, the signal attenuation becomes more severe. Moreover, increasing the bubble concentration further enhances scattering and absorption losses. At 1 MHz, without bubbles, the electric field penetrates approximately 3.5 m into the seawater. However, when bubbles are present, the penetration depth drops to around 1.5 m-nearly half the distance. This substantial reduction indicates that even at lower frequencies, bubbles significantly contribute to the loss of signal strength by scattering and absorbing the RF energy. At 100 MHz, the impact is even more pronounced. In a bubble-free scenario, the RF signal might penetrate roughly 1 m. With bubbles, the penetration depth decreases to about 0.5 m, again reducing the effective propagation range by approximately half. At 1,000 MHz (1 GHz), the effect is most dramatic. The already high attenuation at this frequency causes the electric field to decay within less than 0.5 m in the presence of bubbles. This suggests that, at such high frequencies, the combined scattering and absorption effects of bubbles, possibly coupled with phase shifts and destructive interference, severely compromise signal integrity.

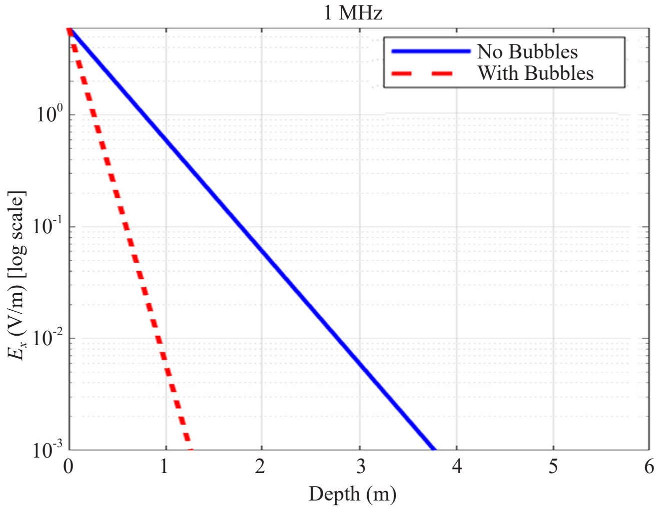

Figure 7. Penetration depth of E_x in seawater with vs. without bubbles at 1 MHz

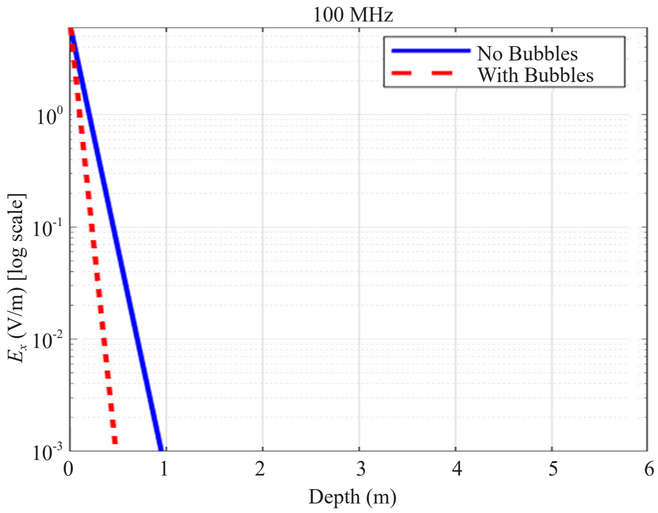

Figure 8. Penetration depth of E_x in seawater with vs. without bubbles at 100 MHz

Overall, these results indicate that bubbles play a critical role in exacerbating path loss in underwater RF communication. The simulations show that bubbles cause a steeper decay in the electric field, effectively halving the penetration depth compared to clear seawater at all frequencies. This trend is more severe at higher frequencies due to increased interaction between the RF waves and the bubbles. Such findings have significant implications for the design and operation of underwater communication systems, emphasizing the need to account for bubble-induced scattering and absorption when choosing the operating frequency and designing the transmission system.

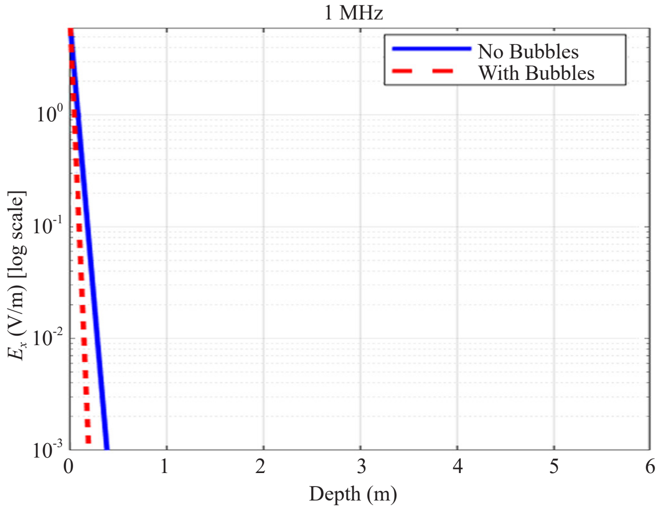

Figure 9. Penetration depth of E_x in seawater with vs. without bubbles at 1,000 MHz

For practical applications with underwater-to-air communication between unmanned underwater vehicles (UUVs) and unmanned aerial vehicles (UAVs), the presence of bubbles in seawater represent challenge for making reliable RF links, when the waves have higher frequencies. The frequency dependence of the attenuation suggests that lower frequencies might be more suitable for communication in bubbly sea water. Other factors, such as bandwidth and data rate, must also need thinking about.

4. Discussion

The simulation results obtained in this study exhibit a strong agreement with the field measurements reported by [46] in their investigation of electromagnetic wave propagation in shallow water coastal environments. In particular, the experimental work by [46] concluded that at a frequency of 1 MHz and a seawater conductivity of 5 S/m, the penetration depth of EM waves was approximately 2 m. In contrast, our simulations conducted at a slightly lower conductivity of 4 S/m also indicate a penetration depth very close to 2 m (with bubble case), despite the additional complexity introduced by bubble-induced attenuation.

One significant advancement in our study is the incorporation of bubble dynamics into the simulation framework. While [46] did not explicitly account for the attenuation effects due to bubbles, our model quantified both the scattering and absorption losses caused by bubbles in seawater. The resulting attenuation not only corroborates the experimental penetration depth observed in [46] work but also provides diagnostic insight into how bubbles further degrade signal propagation. This is particularly important since bubbles, which are prevalent in shallow water environments, can exacerbate the already high conductive losses, thereby affecting the reliability of underwater-to-air communication systems.

Furthermore, in addition to verifying the accuracy of our results at a frequency of 1 MHz, we were able to determine the effect of bubbles at higher frequencies of 100 MHz and 1 GHz. This expanded analysis demonstrates that bubble-induced attenuation becomes even more critical as the frequency increases, offering a more comprehensive evaluation of environmental impacts on EM wave propagation.

The close correspondence between our simulated results and the field experiments validates the robustness of our Monte Carlo simulation approach. By assuming a seawater conductivity of 4 S/m and explicitly modeling the bubble-induced effects, our study not only mirrors the penetration depth reported by [46] but also extends the understanding of attenuation mechanisms in bubbly marine environments. This agreement suggests that our simulation framework is a reliable tool for predicting the performance of underwater electromagnetic communication systems under realistic environmental conditions.

In summary, the comparative analysis underscores that even with variations in the assumed conductivity and the inclusion of bubble effects, our simulation results are consistent with experimental findings. This reinforces the potential of the proposed modeling approach to serve as a predictive tool in the design and optimization of underwater communication systems, offering a more comprehensive evaluation of environmental impacts than previous models.

5. Conclusion

This study focuses on how marine environment, especially seawater bubbles, messes with RF communication between underwater and above UAVs systems. The simulations used show that bubbles mess up signal stuff a lot by scattering and absorbing signals more when frequencies are high. It was found that bubbles close to the water surface really hurt RF signal strength because of Mie and Rayleigh scattering plus reflection. This leads to more path loss and weaker received signals. These results point out big troubles in keeping good underwater-to-air RF communications where there are lots of bubbles in the sea. Bubbles make things uneven, causing heavy scattering and absorption losses which get worse at higher frequencies. Other factors, like wind speed, density of bubbles, and depth, also have a significant impact on the degree of signal attenuation. Due to the strong wind, more bubbles made the situation worse. These findings matter for making underwater communication technology better-using lower RF frequencies might work better in bubbly waters since they don't scatter as much, but it also means giving up some bandwidth and data rates. Future studies should check out smart ways for communication changes like picking frequency or controlling power use along with advanced wave techniques to keep strong RF links in hard marine settings. Furthermore, looking into mixed communication methods using RF with sound or light could also help find fixes for the problems noted here.

Conflict of interest

The authors declare no competing financial interest.

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