Underwater Wireless Sensor Network Communication Using Electromagnetic Waves at Resonance Frequency 2.4 GHz

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Abstract A comprehensive study of electromagnetic waves underwater propagation for a wireless sensor network is introduced in this paper. A mathematical model for the path loss due to attenuation of electromagnetic waves propagates in sea and pure water is given. Reflection from the air-water and water-sand interfaces as a function of distance between sensors and water depth is also introduced. A high gain antenna is required to overcome the high value of path loss. A bow-tie antenna is very common antenna used for underwater wireless communication applications. A high gain bow-tie antenna is designed and simulated using FEKO software. The antenna performance parameters studied in this paper are return loss, voltage standing wave ratio, input impedance and gain.

Keywords Wireless sensor network, electromagnetic waves, reflection, bow-tie antenna, FEKO software, voltage standing wave ratio (VSWR), input impedance, retutn loss (S11) and antenna gain.

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1. Introduction

A wireless sensor network (WSN) is a sensor used to monitor physical or environmental phenomena such as humidity, temperature, sound, vibration, pressure or motion and to cooperatively pass the data through the network of sensors to a main location [1]. As wireless network sensors become smaller in dimension and cheaper researchers are deploy them in environments that are unconventional for electromagnetic signaling [2]. One of those applications for wireless sensor network is underground wireless communication to monitor soil properties and then transmit the collected data to a node on the surface [3]-[8].

Due to high attenuation of electromagnetic signal in water, the underwater wireless sensors rely on sonic transducers for wireless communication [9]-[11]. Sonic transceivers or deploy more nodes are used to overcome high path losses attenuation in water and in this case, the cost is going to be higher. The main advantages of using electromagnetic waves instead of sound are: first, electromagnetic waves reduce the latency due to faster propagation. Second, electromagnetic waves give a high data rate due to high frequency of the wave [12].

In this paper we will discuss the propagation of electromagnetic waves in pure and sea water and study the effect of changing distance between the sensors and change the operating frequency, 2.4 GHz range. The designed bow-tie antenna with a high gain to overcome the path loss due to attenuation in the water is also introduced in this paper.

2. Related Work

There has been some work focusing on electromagnetic waves propagation through soil and water. D. Daniels introduced the empirical attenuation and relative permittivity values for different materials including soil at 100 MHz frequency range [13]. The Electromagnetic field principles of vertical electric dipole over the frequency range from 1 to 10 MHz are analyzed by J. Wit and J. Fuller [14]. The Propagation of electromagnetic waves through soil of frequency range from 1 to 2 GHz is also studied [15]. The propagation of electromagnetic waves in a soil for a frequency range 2.4 GHz is studied by L. Li and *at el* [16]. Also, other effects are studied, such as multipath, soil composition, water content and burier depth.

K. Hunt and *at el*. investigated the propagation of radio waves underwater and between water and air interface. Signal attenuation, multipath due to reflection from the interface surface between air and water and noise due to transmission [2].

3. Antenna Background

Under water communication needs a very efficient antenna for wireless sensor network communication. This antenna must meet a number of requirements required for under water communication to overcome the high value of path loss due. This kind of antenna mast has a high gain, above 10 dB, and should be small in dimension so that it can be fitted on the sensor surfaces. The most common antenna used for under water communication using electromagnetic signals is bow-tie antenna [2].

a) Background

This antenna is popular for frequencies ranging from Ultra High Frequency (UHF), from 300 MHz to 3 GHz, up to the millimetre wave range, from 30 GHz to 300 GHz, and has also found application in arrays. The bow-tie antenna performance is not sensitive to small parameter variations, improving robustness to manufacturing tolerances. While the bow-tie antenna provides reasonable wide-band performance, this is not a high performance antenna; demanding applications may call for more complex designs. The resistively loaded bow-tie antenna is a practical candidate for pulse radiation [21].

b) Physical Description

The bow-tie antenna is easy to construct and can be very robust, but can become restrictively large at low frequencies. The bow-tie antenna is commonly supported by a dielectric substrate, or constructed using suspended metal cut-outs. When a substrate is used, thin, low-permittivity substrates are preferred to avoid the degradation of antenna performance.

4. Underwater Signal Propagation

The signal propagation in water depends on the path loss in water. Received power as a function of transmitted signal, path loss and antenna gain at the receiver end is given from Friis equation as shown in Equation 1 [17].

$$P_{rec}(dBm) = P_i(dBm) + G_t(dB) + G_r(dB) - L_{pathloss}(dB) \qquad (1)$$

where P_t is the transmit power, G_r and G_t are the gains of the receiver and transmitter antenna, $L_{Pathloss}$ is the path loss in water.

The path loss is shown in Equation 2 [18].

$$L_{pathloss}(dB) = L_0(dB) + L_w(dB) + L_{att}(dB) \qquad (2)$$

L_0 is the path loss in air and given by:

$$L_0(dB) = 20\log\left(\frac{4\pi df}{c}\right) \qquad (3)$$

where d is the distance between transmitter and receiver in meter, f is the operating frequency in Hertz and c is the velocity of light in air in meter per second.

$L_w(dB)$ is the path loss due to changing in medium and given by [19]:

$$L_w(dB) = 20\log(\frac{\lambda_0}{\lambda}) \qquad (4)$$

where λ_0 is the signal wavelength in air and calculated ($\lambda_0 = c/f$) and λ is the wave factor and given by ($\lambda = 2\pi/\beta$) and β is the phase shifting constant and calculated as shown in Equation 5.

$$\beta = \omega\sqrt{\frac{\mu\varepsilon'}{2}(\sqrt{1+(\frac{\varepsilon''}{\varepsilon'})^2}+1)} \qquad (5)$$

where ε' and ε'' are the real and imaginary parts of the complex dielectric constant given by ($\varepsilon = \varepsilon' - j\varepsilon''$).

$L_{att}(dB)$ is the path loss due to attenuation in medium and given by:

$$L_{att}(dB) = 10\log(e^{-2\alpha d}) \qquad (6)$$

where α is the attenuation constant and calculated as shown in Equation 7:

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon'}{2}(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1)} \qquad (7)$$

5. Reflection from Water Interfaces

The reflection from the surface and bottom depends on reflection coefficient at the interface between water and air and between water and sand. The reflection coefficient is given by Equation 8 [20].

$$\Gamma = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1} \qquad (8)$$

where ρ_1 and ρ_2 are the density of the first and second medium respectively and v_1 and v_2 are the wave velocity in both mediums.

The reflection loss from the surface and from the bottom is L_{ref} and shown in Equation 9.

$$L_{ref} = -V(dB) = -10\log(V) \qquad (9)$$

where is calculated as shown below:

$$V^2 = 1 + \left(|\Gamma| e^{-\alpha\Delta(r)}\right)^2 - 2|\Gamma| e^{-\alpha\Delta(r)} \times \cos(\pi - (\phi - \frac{2\pi}{\lambda}\Delta(r))) \qquad (10)$$

where r is the reflected path length, $|\Gamma|$ and ϕ are the amplitude and phase of the reflection coefficient respectively and $\Delta(r)$ is the difference between r and d.

where r can be calculated as follow:

$$r = 2\sqrt{H^2 + (\frac{d}{2})^2} \qquad (11)$$

Figure 1. illustrates the three-path channel model, including reflection from the air and water interface and from

the sand.

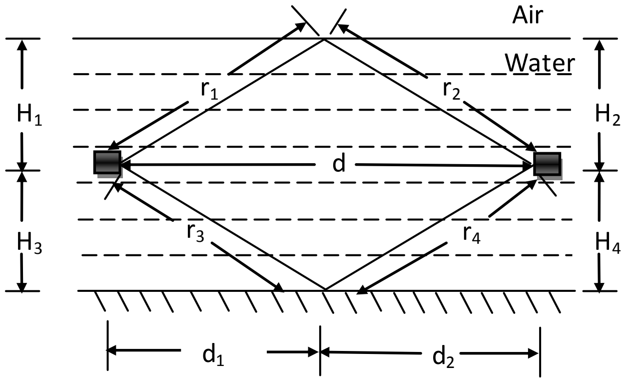

Figure 1. Three-path channel model.

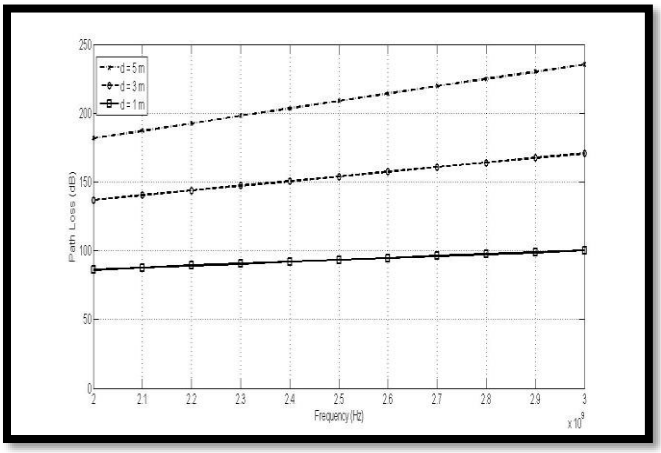

Figure 2. Path loss (dB) as a function of resonance frequency (GHz) for different distance between two sensors (m) for pure water.

where d is the distance between two sensors, H is the distance between surface and the sensor and r is the distance between the sensor and the reflection point.

6. Results

The effect of frequency on the path loss for different values of distance between sensors using pure and sea water is illustrated in the following sections and then the comparison between pure and sea water is also given.

6.1 Path Loss Calculation

The total path loss due to communication between sensors without reflection loss is shown in the next sections.

a) Pure Water

Water differs from air in a having higher conductivity, higher density and higher permittivity. The relative permittivity of pure water is ε`=79, tangent loss is ε``=0.924 the density is 1000 kg/m^3 at 2.4 GHz.

The effect of frequency on the path loss for different values of distance is illustrated in Figure 2. As clearly shown in the figure, as the frequency increases the path loss is also increases for the same value of distance. For 1, 3 and 5 m distance, the path loss is increased by almost 50 dB for each 2 m change in distance. In Figure 3. the effect of distance on a path loss is illustrated for different values of frequencies, 2, 2.4 and 3 GHz.

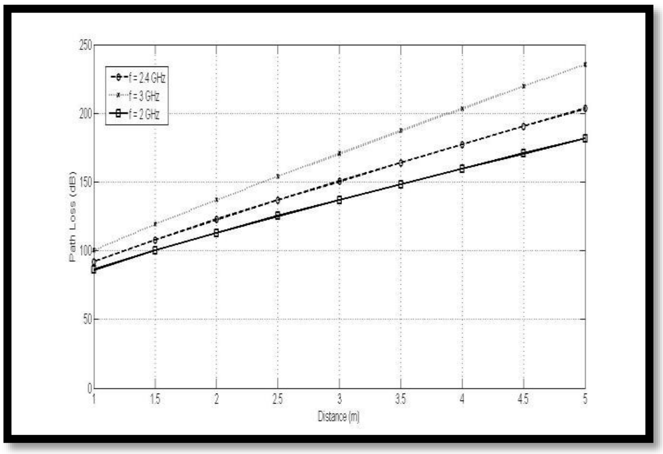

Figure 3. Path loss (dB) as a function of distance between two sensors (m) as a function of resonance frequency (GHz) for pure water.

b) Sea Water

The relative permittivity of sea water is ε`=80.4, tangent loss is ε``=1.527 the density is 1033 kg/m^3 at 2.4 GHz. The relative permittivity value depends on the concentration of the salt in the sea water, in this case the concentration of the salt is 3% which is a normal value.

The frequency as a function on the path loss for different values of distance is illustrated in Figure 4. For lower permittivity for sea water, the path loss is lower than pure water. The change in the path loss due to change in distance is almost 30 dB for each 2 m. In Figure 5. the effect of distance on a path loss is illustrated for different values of frequencies, 2, 2.4 and 3 GHz.

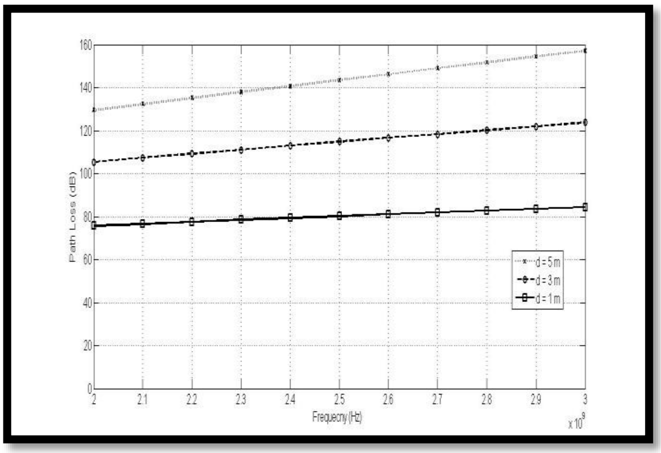

Figure 4. Path loss (dB) as a function of resonance frequency (GHz) for different distance between two sensors (m) for seawater.

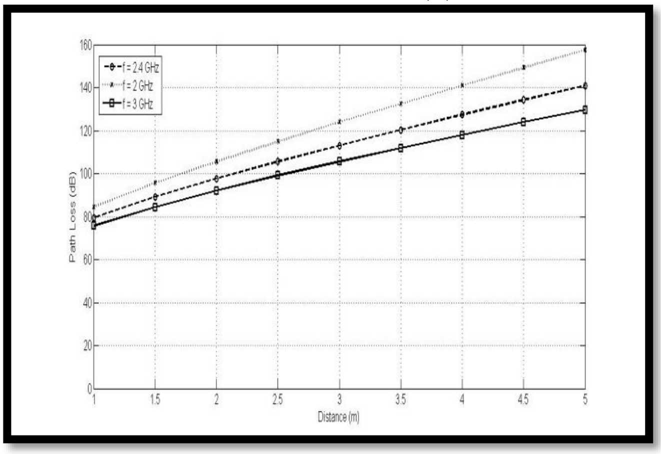

Figure 5. Path loss (dB) as a function of distance between two sensors (m) as a function of resonance frequency (GHz) for seawater.

c) Comparison between pure and sea water

The comparison between pure and sea water path loss as a function of frequency at distance 3 m is shown in Figure 6. The path loss for pure water is higher than in sea water by almost 20 dB at the same distance. At frequency 2.4 GHz, the path loss for pure water is also higher than sea water as a function of distance between sensors as illustrated in Figure 7.

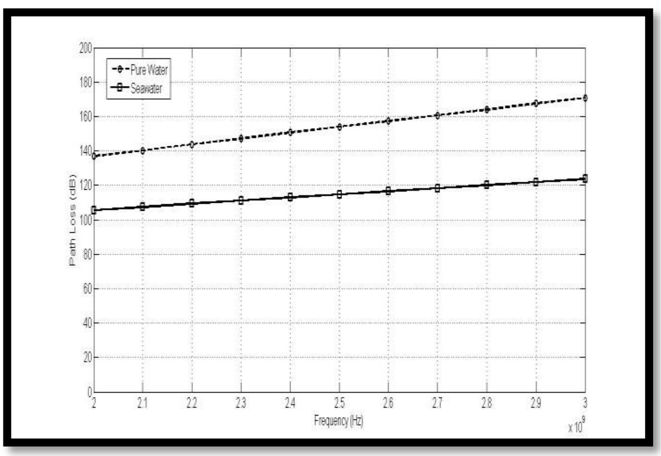

Figure 6. Path loss (dB) as a function of resonance frequency (GHz) for pure water and seawater at a distance 3 m.

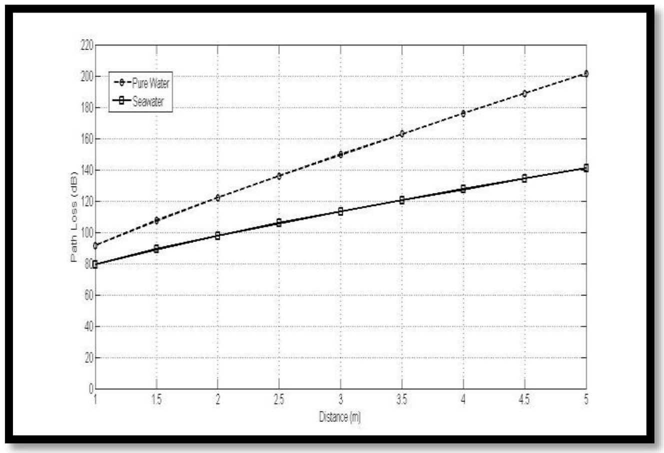

Figure 7. Path loss (dB) as a function of distance between two sensors (m) for pure water and seawater at a resonance frequency 2.4 GHz.

6.2 Reflection Calculation

An extra loss due to reflection is obtained. The reflection from water air interface and reflection from the water ground interface are studied in this section. Some approximations are assumed here to simplify the simulation as in Figure 1. as follow:

1. The sensors are in the middle of the water height, $H_1= H_2= H_3= H_4=H$.
2. All multipath are equal, $r_1= r_2= r_3= r_4=r$.
3. Distances $d_1= d_2 = d$.

a) Pure Water

The path loss due to reflection from water surface interface is calculated as a function of distance between sensors for different values of height and at 2.4 GHz resonance frequency as shown in Figure 8. As shown in Figure 8. the effect of height on the reflection loss is very high value for a shallow water and almost negligible for a deep water, *H* more than 1 m. The same conclusion is obtained in Figure 9. Path loss due to reflection as a function of frequency for different values of *H* at distance 3 m is illustrated in Figure 8.

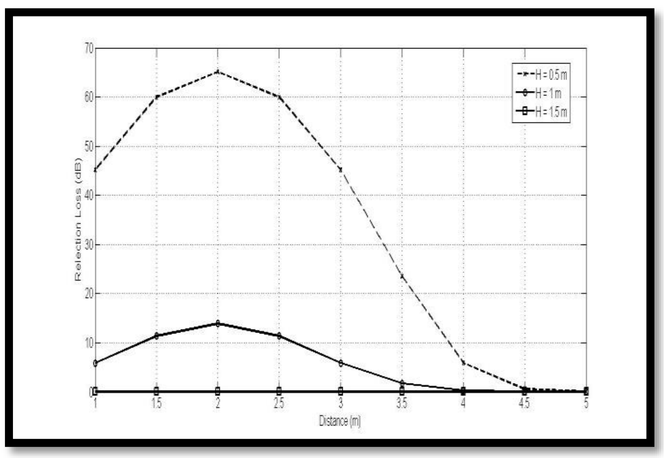

Figure 8. Path loss (dB) as a function of distance between two sensors (m) for pure water at a resonance frequency 2.4 GHz and different values of *H*.

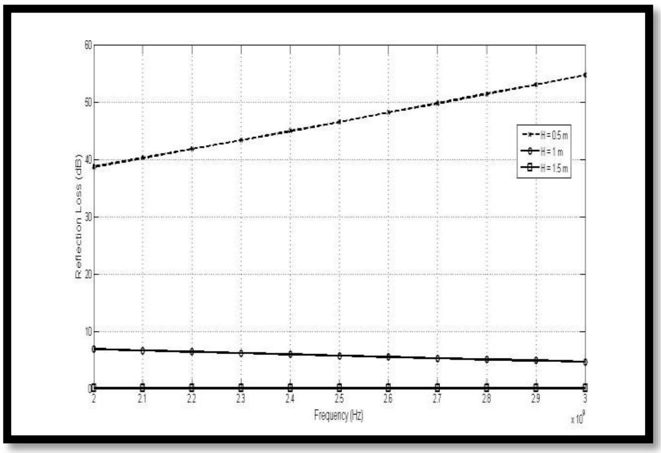

Figure 9. Path loss (dB) as a function of resonance frequency (Hz) at distance 3 m for pure water and different values of *H*.

b) Sea Water

The same Figures 10 and 11 are obtained for sea water, but the path loss due to reflection for sea water is lower value than pure water.

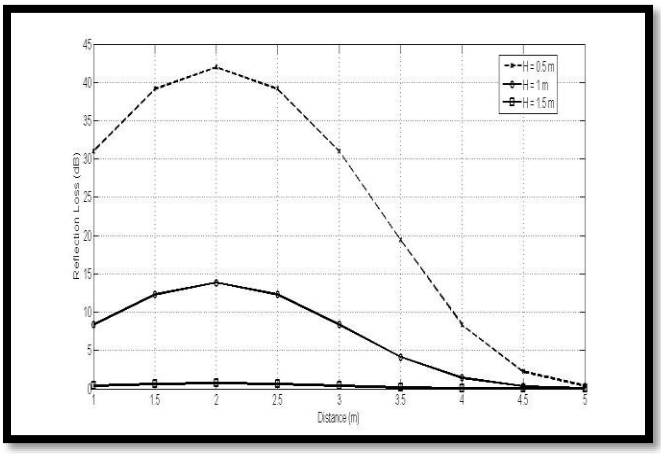

Figure 10. Path loss (dB) as a function of distance between two sensors (m) for sea water at a resonance frequency 2.4 GHz and different values of *H*.

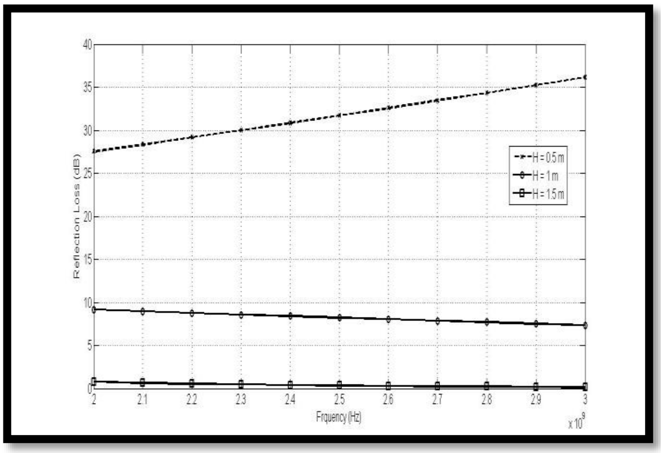

Figure 11. Path loss (dB) as a function of resonance frequency (Hz) at distance 3 m for pure water and different values of *H*.

c) Antenna Design

Bow-tie antenna operates at 2.4 GHz design is shown in Figure 12. FEKO software is used to design and simulate this antenna. The dimensions of the designed antenna are as follow: arm length is 67 mm, flare angle is 130^0, substrate height is 3 mm, substrate length is 167.5 mm, substrate width is 167.5 mm and the dielectric constant height is 0.8 mm.

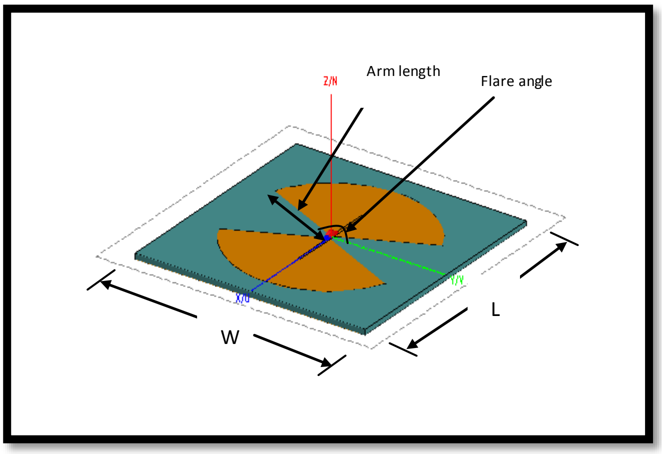

Figure 12. Designed bow-tie antenna operates at 2.4 GHz.

Figure 13 shows the radiation pattern of bow-tie antenna operates at 2.4 GHz. The radiation pattern is almost omni-directional pattern, where the radiated energy is equal in all directions. The return loss is shown in Figure 14. Return loss value is -14 dB at 2.4 GHz which is efficient for using in underwater use, should be less than -10 dB in most of underwater applications. Figure 15 shows the voltage standing wave ratio for the designed antenna. The VSWR value is 1.5 at 2.4 GHz which is very efficient in manufacture process of the bow-tie antenna. Real part of input impedance is shown in Figure 16; the real value of input impedance is almost 75 ohm at 2.4 GHz. The maximum gain is obtained at 2.4 GHz for the designed antenna as shown in Figure 17.

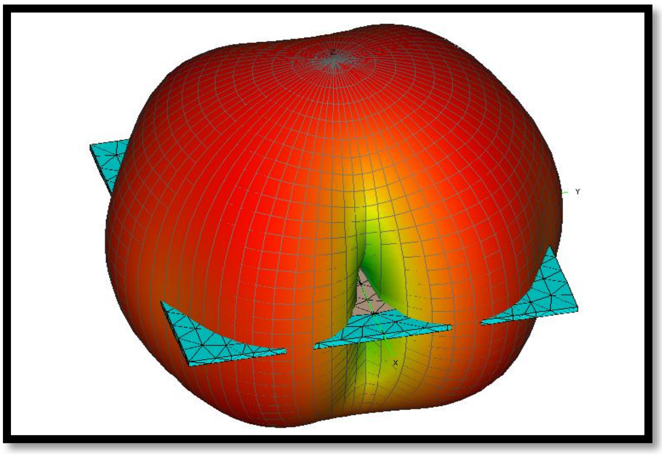

Figure 13. Radiation pattern of bow-tie antenna operates at 2.4 GHz.

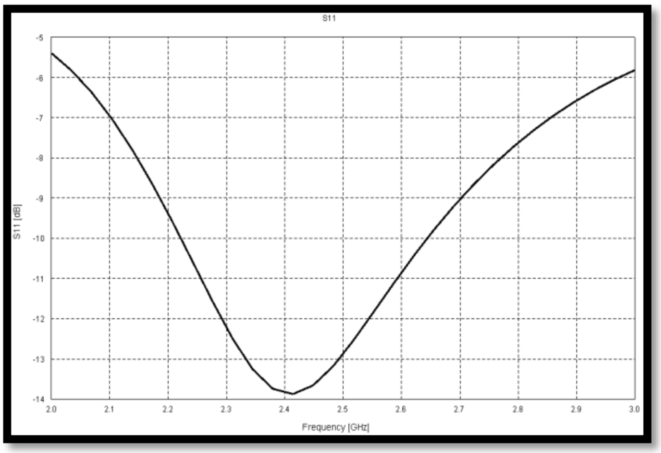

Figure 14. Return loss (S11) as a function of frequency (GHz).

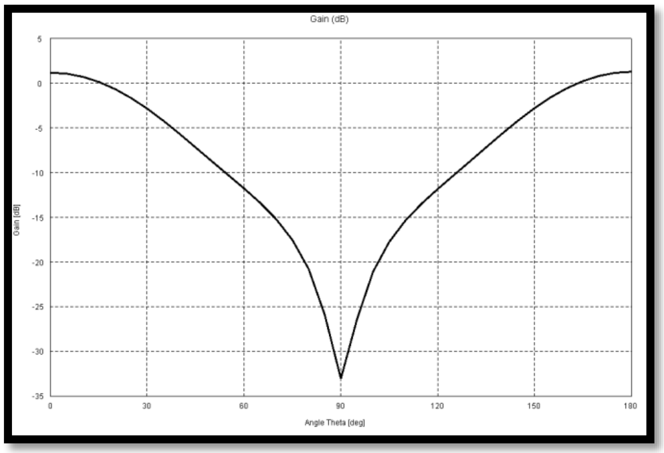

Figure 17. Antenna gain as a function of frequency (GHz).

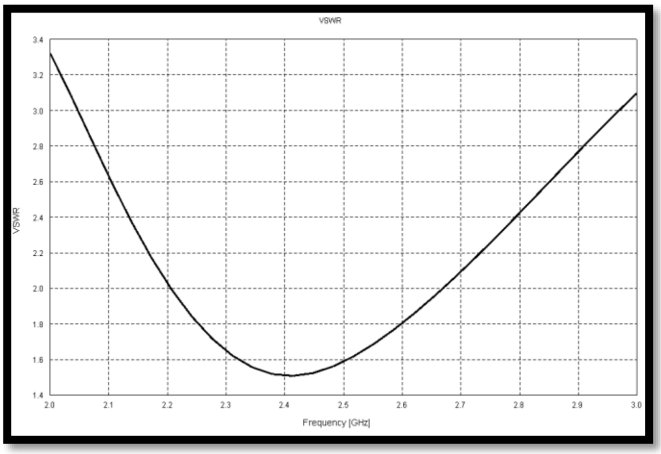

Figure 15. Voltage standing wave ratio as a function of frequency (GHz).

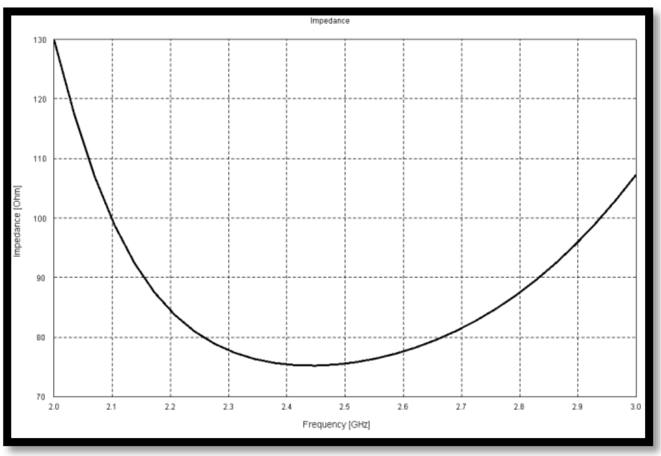

Figure 16. Input impedance as a function of frequency (GHz).

7. Conclusion

A mathematical model for path loss due to attenuation of electromagnetic waves propagates in pure and sea water at 2.4 GHz frequency is introduced in this paper. The reflection of electromagnetic waves at the water interface is given as a function of water depth and distance between sensors. For lower permittivity for sea water, the total path loss is lower than values pure water.

The reflection from water interface is negligible in case of deep water and has a great effect in case of shallow water, in the range of 1 m depth.

A high gain bow-tie antenna is designed and simulated using FEKO software. Return loss, voltage standing wave ratio, real part of input impedance and gain is also given in this paper. The antenna gain is -30 dB at 2.4 GHz, which is very high value for underwater wireless communication to overcome the high path loss due attenuation.

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