

# A matched Bow-tie antenna at 433MHz for use in underwater wireless sensor networks

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**Abstract.** Electromagnetic (EM) wave propagation underwater is been disregarded because of attenuation at high frequencies, however the theory predicts that propagation is possible at some useful distance in the lower Industrial, Scientific and Medical (ISM) band. Common transceivers rely on narrowband antennas and matching circuit. The aim of this paper is to design a broadband 433MHz bow-tie antenna and experiment it in air and water without a matching circuit. This antenna could be attached to wireless transceivers and form a Wireless Sensor Network for deployment in various underwater applications. The bow-tie antennas were designed, simulated and constructed in laboratory. Experiments were setup carefully by using a completely isolated transmitter from electronics to avoid airborne transmission. The 433MHz. bow-tie proved its suitability for use in Underwater.

## 1. Introduction

Electromagnetic (EM) communication has been disregarded due to attenuation at high frequencies. With a propagation velocity up to  $3 \times 10^7$  m/s, EM waves propagation offer many advantages over conventional acoustic techniques, including bandwidth, data rate and better transmission across boundaries. Attenuation has been the biggest obstacle in radio propagation underwater. However in [1] it was demonstrated both, experimentally and theoretically that EM wave propagation is possible through the water column at useful distances in the lower unlicensed Industrial, Scientific and Medical bands. In the context of deploying Wireless Sensor Network in unusual places for electromagnetic wave propagation, further experimental research in [2] demonstrated communication underwater with off the shelf radio transceivers. It is been concluded that the main factors enabling the increase in communication range were the antenna and the operating frequency. In [3], experiments involving narrowband antennas built for the 433MHz ISM band, this frequency of operation was targeted because it presents equilibrium in attenuation and data rate transmission in ISM bands, experiments demonstrated that type and size of antenna also have an impact on underwater communication systems. Simulation of a monopole antenna in a water environment in [4] illustrated how narrowband antenna designed for air presents a shift in the frequency of operation with respect to the return loss due to the change of medium air/water making the antenna almost not transmitting in its new environment (water) at the frequency designed for. Loop antennas were used in [5] and [6] and other than being directional antennas, they strongly responds to magnetic fields making them more destined for seawater.

Return Loss (RL) also known as S11(dB) is a good measure of how much power is reflected back (logarithmic scale) from the terminal [7]. It is known that a good antenna must be at least -10dB to allow 90% transfer of energy. Therefore this will be the targeted RL for the underwater antenna.



Impedance matching is an important aspect in any antenna design and the use of a matching circuit is common for air designed antenna. As the antenna impedance is different when the antenna is in air or water the impedance measurements must be taken with the antenna in the medium it will operate to design the appropriate matching circuit. Furthermore antennas utilising a matching circuit may suffer from complete signal loss if any changes in temperature and salinity occur in the water due to the high dielectric property of water.

Another technique for choosing an underwater antenna is to use a broadband antenna design that can accommodate the change in such a heavy dielectric medium. With dipoles being one of the simplest but widely used types of antenna, the bow-tie is one form that potentially has the correct properties [7] to be used as an underwater antenna. The aim of this paper is to validate the use of this antenna design to form an underwater wireless sensor network.

## 2. Electromagnetic wave propagation underwater

### 2.1. Permittivity of water

Permittivity of a material is a characteristic which describes how it affects any electric field set up in it. When the material is lossy (dissipates energy), the relative permittivity is a complex quantity [8] given by Equation (1).

$$\epsilon r = \epsilon' r - j\epsilon'' r \quad (1)$$

The real part is related to the energy stored within the medium. Because water is a polar molecule and rotates when exposed to an alternating electric field, the imaginary part is then associated to the dissipation of the energy due to collisions during that rotation and to the loss due to free charge conduction. At 433MHz, the relative complex permittivity of water is  $80.17 - j1.92$  [9]. These values correspondent to permittivity of water with salinity  $S=0$ ppt and temperature  $T=20^\circ\text{C}$ . Meissner and Wentz introduced in [10] a model as in Equation (2) with double Debye relaxation wavelength that they consider as a necessary parameter to provide an accurate fit for the dielectric constant over a wider frequency range than the single Debye model does.

$$\epsilon(T, S) = \frac{\epsilon_s(T, S) - \epsilon_l(T, S)}{1 + i \frac{\nu}{\nu_1}(T, S)} + \frac{\epsilon_l(T, S) - \epsilon_\infty(T, S)}{1 + i \frac{\nu}{\nu_2}(T, S)} + \epsilon_\infty(T, S) - i \frac{\sigma(T, S)}{(2\pi\epsilon_0)\nu} \quad (2)$$

With  $i = \sqrt{-1}$ ,  $\nu$  the radiation frequency in GHz,  $\epsilon_s(T, S)$  the static (zero frequency) dielectric constant,  $\epsilon_\infty$  the dielectric constant at infinite frequencies,  $\epsilon_l$  the intermediate frequency dielectric constant,  $\epsilon_0$  the vacuum electric permittivity  $= 8.854 \times 10^{-12}$ ,  $\nu_1(T, S)$  and  $\nu_2(T, S)$  the first and second Debye relaxation frequencies,  $T$  the temperature in  $^\circ\text{C}$ ,  $S$  the salinity in ppt (parts per thousands).

Using Equation (2), for operating frequency at ISM band 433MHz the permittivity of water with salinity concentration  $S=0.2345$ ppt (tap water used for the tank experiment), water with  $S=0.29011$ ppt (measured value in Liverpool Stanley Canal) and water with  $S=0$ ppt ( $\approx$  distilled water), are calculated and displayed in Table 1.

**Table 1** Real and Imaginary parts of permittivity at 433MHz ISM freq in different water environment

ISM Frequency	Permittivity of water with $S=0.29011$ ppt ( $\approx$ canal water), $T=15^\circ\text{C}$		Permittivity of water with $S=0.2345$ ppt ( $\approx$ tap water in tank), $T=15^\circ\text{C}$		Permittivity of water with $S=0$ ppt ( $\approx$ distilled water), $T=15^\circ\text{C}$	
	Real	Imaginary	Real	Imaginary	Real	Imaginary
433MHz	81.930	4.177	81.945	3.81	82.010	2.27

Those values are used to calculate the effective conductivity ( $\sigma_{\text{eff}}$ ) and the attenuation ( $\alpha$ ).

## 2.2. Attenuation of signal in water

The complex propagation constant  $\gamma$  describes the behaviour of an EM wave [11] is defined in Equation (3) with  $\alpha$  attenuation constant and  $\beta$  phase constant:

$$\gamma = \alpha + j\beta \quad (3)$$

The main factor that effects EM propagation underwater is the attenuation. Attenuation refers to the decrease in the magnitude of a signal as it propagates through a medium (e.g. air, rock, water). Attenuation may be due to the spreading of energy as it propagates away from its source as well as due to the medium itself absorbing the energy of the signal. Attenuation of a plane wave in a lossy medium can be calculated from the homogeneous Helmholtz equation which leads to Equation (4).

$$\alpha = \omega \sqrt{\mu \epsilon'} \sqrt{0.5 \sqrt{1 + (\sigma_{\text{eff}} / \omega \epsilon')^2} - 1} \quad (4)$$

With  $\alpha$  the attenuation in Nepers/m,  $\omega$  the frequency in radians,  $\mu$  the permeability of the medium in  $\text{N/A}^2$ ,  $\epsilon'$  the permittivity of the medium in  $\text{F/m}$  as  $\epsilon' = \epsilon_0 \epsilon'_r$  and  $\sigma_{\text{eff}}$ , the effective conductivity in  $\text{S/m}$  as  $\sigma_{\text{eff}} = \omega \times \epsilon_0 \epsilon''_r$

Using permittivity values from Table 1 in Equation (4), attenuation ( $\alpha$ ) is then calculated for operating frequency at 433MHz ISM band in the water with salinity concentration  $S=0.2345\text{ppt}$  (tap water used for the tank experiment), water with  $S=0.29011\text{ppt}$  (measured value in Liverpool Stanley Canal) and water with  $S=0\text{ppt}$  ( $\approx$  distilled water), and displayed in Table 2.

**Table 2** Attenuation of signal at 433MHz ISM frequency in different water environment

ISM Frequency	Attenuation (dB/m) of water with $S=0.29011\text{ppt}$ ( $\approx$ canal water), $T=15^\circ\text{C}$	Attenuation (dB/m) of water with $S=0.2345\text{ppt}$ ( $\approx$ tap water in tank), $T=15^\circ\text{C}$	Attenuation (dB/m) of water with $S=0\text{ppt}$ ( $\approx$ distilled water), $T=15^\circ\text{C}$
433MHz	18.178	16.599	8.465

According to table 2 Attenuation in water with salinity equals or smaller than canals water and freshwaters salinities are not high in the 433 MHz ISM band and seems encouraging for building a wireless sensor network using commodity nodes. As the important remaining factor to enable communication in water is the antenna, a potential type “bow-tie” is designed, constructed and tested.

## 3. Research approach

At first, using High Frequency Structure Simulator, a bow-tie antenna is designed and iterated to resonate at 433MHz in air with at least a return loss of -10dB. A standard 1.6mm thickness Printed Circuit Board made of 0.0356 thick copper sheet and FR4 glass-reinforced epoxy laminate sheet was used for the antenna which is modelled in a  $0.30\text{m}^3$  box of air. Then a bound body of water with conductivity 0.02 S/m (approximated value of tap water) and absorbent boundary condition was used to model the antenna in a water environment.

Then, the antenna is sketched in Eagle PCB software and transferred into the Computer Numerical Control routing machine Bungard CCD2 for prototypes in the sensors laboratory.

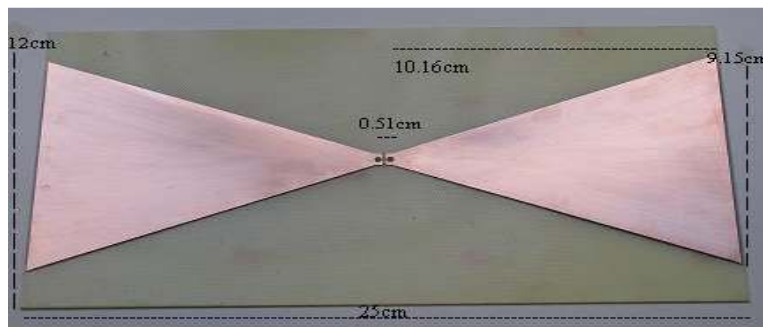


Figure 1 Angle-view of the Bow-tie antenna constructed in laboratory

Finally, the 433MHz designed bow-tie antenna constructed as shown in Figure 1 is tested in a plastic tank filled with 1200L of tap water with conductivity of 0.035S/m and temperature of 15°C. The antenna is fully waterproofed with glue and connected with an RG58 cable to a MS2024A Anritsu Network Analyzer through a plastic waterproofed container and a hose (Figure 2). This setup is used to collect the S11 antenna parameters. For collecting S21 parameters, the experimental setup in Figure 3 involves on the transmitting side an electronic circuit (voltage controlled oscillator, a variable resistor, a voltage regulator and a pack of batteries) in a plastic waterproofed container connected to the bow-tie antenna and on the receiver side a vertically moveable waterproofed bow-tie and plastic container connected to a 8594E HP Spectrum Analyzer through an RG58 cable in hose, supported by a PVC tube. The transmitter is completely submerged with no RF cable floating in air/water. This setup eliminates airborne transmission.

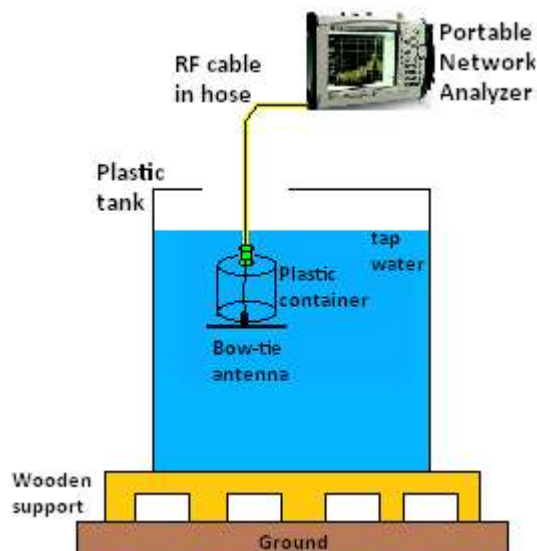


Figure 2 Experiment setup in tank for S11

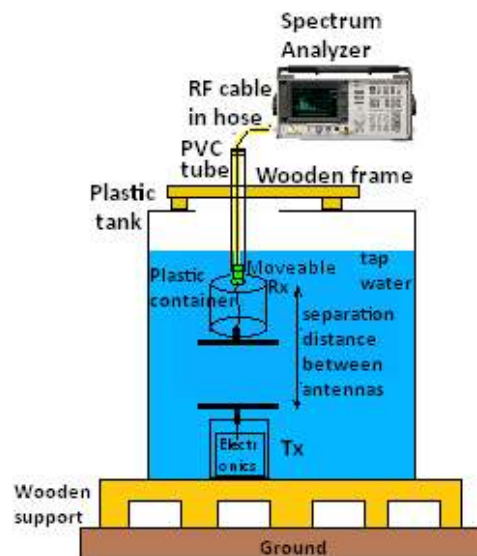


Figure 3 Experiment setup in tank for S21

#### 4. Results

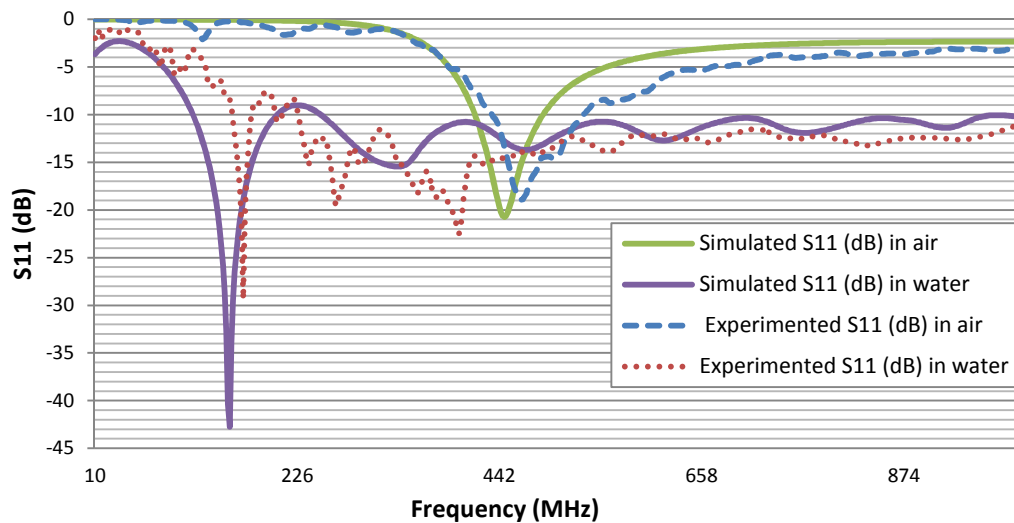


Figure 4: Simulated and experimented S11(dB) of a bow-tie antenna in air and in water

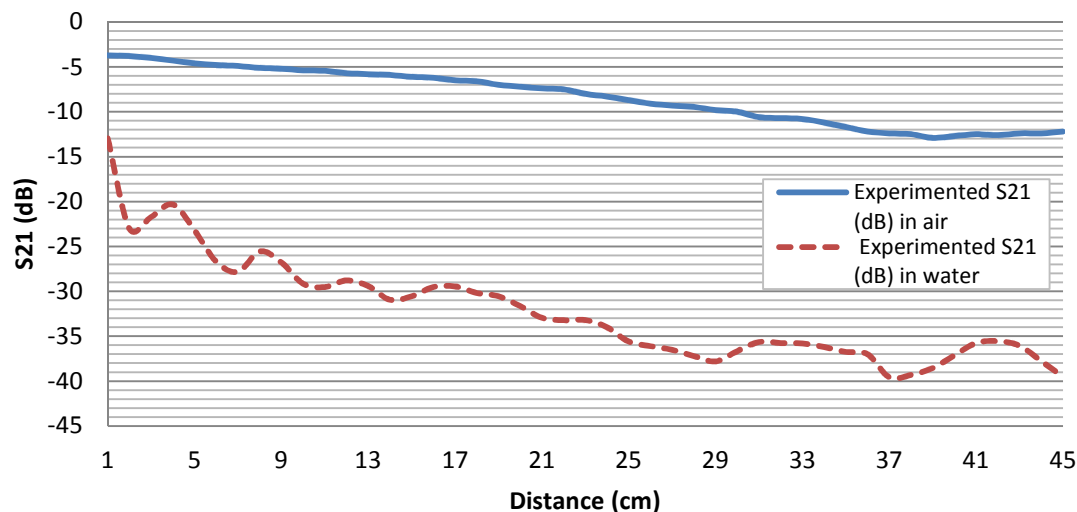


Figure 5: Preliminary experimental S21 (dB) of two bow-tie antennas in air and in water

#### 5. Discussion

The HFSS simulation and experimental RL results are compared for the 433MHz designed bow-tie antenna in air and water in Figure 4. In air, the simulated antenna exhibits a RL of -16dB at 433MHz which means that more than 95% of the power is transmitted. In water, the simulation presents a sharp valley at low frequencies of 154MHz with a high value -43dB of RL and bandwidth of 90MHz. More importantly, is the behaviour of that antenna from 226MHz up to 1GHz shown as a ripple region. In this region the antenna becomes broadband with at least -10dB RL. Simulation results in air and water envisaged the bow-tie antenna to be a good candidate for development of an underwater WSN antenna. Experimental results in air show a slight shift of the valley however at 433MHz the RL is -10dB and lies within the targeted RL, this is also in good agreement with the simulation. In water, the experimental curve follows the overall shape of the simulated curve and the ripple region in figure 4 shows the broadband aspect of the antenna and therefore agreement with the simulation and suitability to be used as an underwater antenna.

Most of underwater RF experiments in the literature review utilise on the transmitting side a signal generator to create the signal to the antenna through a RG58 RF cable. Trials with this type of setup have shown that the RF cable acts as an antenna and by consequent results in erroneous data received from airborne transmission. In this paper for collecting S21 parameters, the transmitter is completely submerged with no RF cable floating in air/water to eliminate airborne transmission.

Figure 5 displays S21 preliminary results for the bow-tie antenna in air and in water over a distance of 45cm. The graph shows that in air the antenna signal strength has dropped 10dB over 45cm separation distance. However it seems that this is the maximum loss the antenna will suffer from in air. In water, at 1cm the signal loses 10dB compared to the air environment. This value added to the power of the VCO (6dB at 433MHz) is in agreement with the theoretical attenuation value in table 2 (16.6dB). Two regions can be distinguished a near-field region up to 30cm separation distance and a far-field region onwards. The near field region includes the totality of the signal drop. In the far field the signal lies in the -40dB whereas most common transceivers have a sensitivity of -100dBm.

## 6. Conclusion

In this paper the steps that can permit a bow-tie antenna to work in water without a matching circuit has been presented from design to practice. Preliminary through water transmission experiment is carried on to support the use of the constructed 433MHz bow-tie in a two way communication sensor system. Further underwater trials are planned in a canal to determine the maximum separation distance and the path loss at 433MHz through water.

## 7. References

- [1] A. A. Abdou, A. Shaw, J. Cullen, S. Wylie, A. Mason, and A. Al-Shamma, "A Review of Underwater EM Wave Propagation to Investigate the Development of a Through Water WSN," in *6th Built Environment And Natural Environment*, 2011, pp. 1–6.
- [2] A. A. Abdou, A. Shaw, A. Mason, A. Al-Shamma, J. Cullen, and S. Wylie, "Electromagnetic (EM) Wave Propagation for the Development of an Underwater Wireless Sensor Network (WSN)," in *Sensors, 2011 IEEE*, 2011, no. 1, pp. 1571 – 1574.
- [3] A. A. Abdou, A. Shaw, A. Mason, A. Al-Shamma, S. Wylie, and J. Cullen, "Wireless Sensor Network for Underwater Communication," in *Wireless Sensor Systems*, 2012, pp. 3–8.
- [4] A. A. Abdou, A. Shaw, A. Mason, A. Al-Shamma, S. Wylie, and J. Cullen, "Antennas Experiment , Design and Simulation for Underwater EM Wave Propagation at ISM Frequency Bands.," in *Built Environment and Natural Environment*, 2012, pp. 1–6.
- [5] J. H. Goh, A. Shaw, and A. I. Al-Shammaa, "Underwater wireless communication system," *Journal of Physics: Conference Series*, vol. 178, p. 012029, Jul. 2009.
- [6] A. Shaw, A. I. Al-Shammaa, S. R. Wylie, and D. Toal, "Experimental Investigations of Electromagnetic Wave Propagation in Seawater," in *2006 European Microwave Conference*, 2006, no. September, pp. 572–575.
- [7] Y. Huang and K. Boyle, *Antennas from theory to practice*. John Wiley & Sons, Ltd, 2008.
- [8] R. W. P. King and G. S. Smith, *Antennas in Matter*. Cambridge, MA: MIT Press, 1981.

- [9] D. Lide, *CRC Handbook of Chemistry and Physics*, 2010th ed. CRC Press/ Taylor and Francis, 2010.
- [10] T. Meissner and F. J. Wentz, "The complex dielectric constant of pure and sea water from microwave satellite observations," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 42, no. 9, pp. 1836–1849, Sep. 2004.
- [11] D. K. Cheng, *Field and Wave Electromagnetics*, Second. Addison Wesley Publishing Company, 1989, p. 367.