Short Paper: Antennas for Mussel-Based Underwater Biological Sensor Networks in Rivers

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ABSTRACT

Researchers are working on using freshwater mussels as biological sensors. A sensor placed on the mussel detects the mussel's rhythmic opening and closing, or gape. Changes in the gape can indicate changes in the mussel's environment. We plan to attach gape sensors, microcontrollers, and radios to mussels and place them back in their natural environment. Small, inexpensive radios operating in the Industrial, Scientific and Medical (ISM) bands will provide the physical link of an underwater wireless sensor network (WSN). Despite the attenuation radio waves experience in water, the low cost of these radios should allow us to deploy enough to set up a reliable communications network. While commercially available radios can be used underwater with waterproofing, antennas designed for use in air are unsuitable for use in water, because of the different electromagnetic properties of water and air. We designed dipole, loop, and folded dipole antennas for use in water and attached these to transmitters. We measured the power transmitted by the antennas by immersing the transmitters in a tank of water and measuring the received power at different distances using a small dipole antenna attached to a spectrum analyzer. The distance between the antennas was precisely controlled with a motorized *xy* positioner.

Categories and Subject Descriptors

C.2.0 [**Computer Communications Networks**]: General – *data communications* C.3 [**Computer Communications Networks**]: Special-purpose and applications-based systems – *Real-time and embedded systems*

General Terms

Measurement, Design, Experimentation

Keywords

Antenna, electromagnetic, underwater, radio, communications, wireless sensor network

WUWNet'10, Sept. 30 – Oct 1, 2010, Woods Hole, MA, USA.

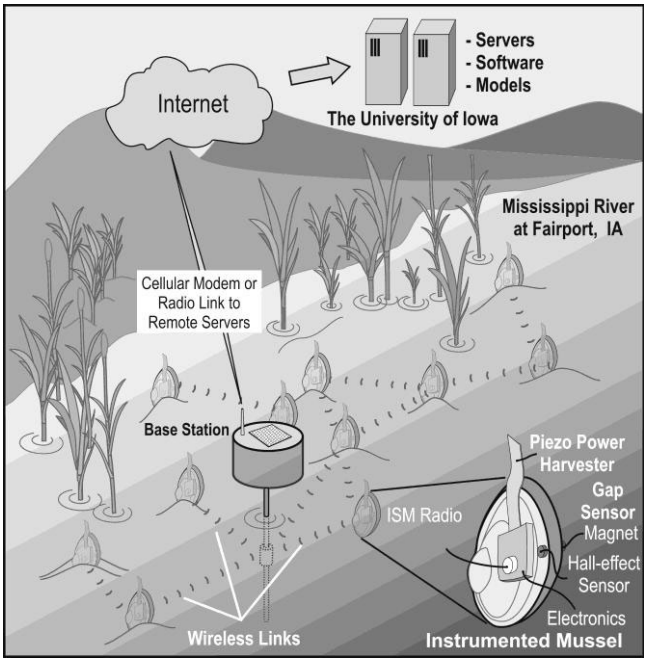

Figure 1. Researchers at The University of Iowa are creating underwater biological sensor networks, where mussels form the nodes in the network. In this paper, we focus on effective antennas for the ISM radios that provide the physical link between the nodes.

1. INTRODUCTION

At The University of Iowa we are designing a system using freshwater mussels as biological sensors [1] and [2], Figure 1 depicts the general approach. Mussels are instrumented with Hall-effect sensors and magnets. The sensors detect the rhythmic opening and closing of the mussels (called the mussel gape). Changes in the mussel gape can indicate environmental stress, changes in mussels' food supply, or may serve as a proxy for turbidity. Additionally, mussels collectively have the potential to significantly affect dissolved oxygen content and nitrate levels in river reaches. There are several examples of tethered mussel biological sensors [3], [4], and [5]. Our vision is to instrument mussels and place them back in their natural environment, but untethered. Small, inexpensive radios operating in the *Industrial*,

Scientific and Medical (ISM) bands will provide the physical link of an underwater *wireless sensor network* (WSN). The microcontrollers and radios on the mussels cooperate, using the WSN paradigm, and deliver data packets to a base station that relays the information to remote serves where the gathered information is analyzed.

The attenuation of electromagnetic waves at ISM frequencies is high (13.6 dB/m at 315 MHz, 17.6 dB/m at 433 MHz and 266 dB/m at 2.4 GHz). However, our calculations show that one can still achieve reliable communication over distances of up to 15 feet in river water at the lower (315- and 433 MHz) frequencies.

2. ELECTROMAGNETIC PROPAGATION IN WATER

The propagation constant γ determines the changes in an electromagnetic wave as it propagates in a given direction [6] and [7]. The propagation constant is given by

$$\gamma = \sqrt{j\omega\mu(j\omega\varepsilon + \sigma)} \quad (1)$$

where ω is the angular frequency, μ is the magnetic permeability, and ε the electric permittivity. The propagation constant has a real attenuation constant α and an imaginary phase constant β [6]

$$\gamma = \alpha + j\beta \quad (2)$$

$$\alpha = \omega\sqrt{\mu\varepsilon}\sqrt{\frac{1}{2}\left(\sqrt{1 + (\sigma/\omega\varepsilon)^2} - 1\right)} \quad (3)$$

$$\beta = \omega\sqrt{\mu\varepsilon}\sqrt{\frac{1}{2}\left(\sqrt{1 + (\sigma/\omega\varepsilon)^2} + 1\right)}. \quad (4)$$

The attenuation constant determines the rate of decay of propagating electromagnetic wave and the phase constant determines the rate of phase change. The two major differences between air and water are in conductivity and electrical permittivity. Unlike air, water is a conducting medium and dissipates energy as heat when an electromagnetic wave propagates through the water. The conductivity of salt water is about 4 S/m, [8] but the conductivity of the Iowa River is much less, about 0.05 S/m. In our experimental setup (see below) the measured conductivity of the water was about 0.034 S/m. The relative electrical permittivity of a medium is the ratio of the electrical permittivity of that medium to that of a vacuum. Relative permittivity is a complex quantity [9].

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \quad (5)$$

The relative permittivity of air is about one. The relative permittivity of water is about 80 at microwave frequencies, one of the highest of any substance. At the frequency we used in the experiments, 433 MHz, the relative permittivity of water is 80.17 –j1.924 [10]. Water is a polar molecule and rotates when exposed to an alternating electric field. The imaginary part of the relative permittivity is a measure of the energy lost due to collisions during that rotation. The losses due to conductivity and the imaginary portion of conductivity can be considered an effective conductivity [9]

$$\sigma_{eff} = \sigma + \omega\varepsilon'' \quad (6)$$

The energy loss can be greater than conduction losses at high frequencies. For our experiment the effective conductivity is 0.8 = 0.034 + 0.046. Another important constant for electromagnetic propagation is intrinsic impedance η, the ratio of the transverse electric and magnetic fields, which determines power transfer.

$$\eta = \sqrt{j\omega\mu/(j\omega\varepsilon + \sigma)} \quad (7)$$

Water exhibits two types of properties, depending on whether the frequency is greater or less than the transition frequency [11]

$$\omega_t = \sigma_{\text{eff}}/\varepsilon \quad (8)$$

When $\omega >> \sigma/\omega_t$ which is the case in freshwater for the commodity motes we plan to use, the attenuation constant has reached a maximum and would be independent of frequency if the effective conductivity was a constant.

$$\alpha \cong (\sigma_{\text{eff}}/2)\sqrt{\mu/\varepsilon}\,. \quad (9)$$

The propagation constant and intrinsic impedance are approximately those of a lossless dielectric [11]

$$\beta \cong \omega\sqrt{\mu\varepsilon} \quad (10)$$

$$\eta \cong \sqrt{\mu/\varepsilon} \quad (11)$$

Because the permittivity of water is about 9 times that of air, the intrinsic impedance is about a 1/9 that in air and the propagation constant is about 9 times that in air. From the expression for wavelength

$$\lambda = 2\pi/\beta \quad (12)$$

it follows that the wavelength λ in water is about an 1/9 that in air. For a frequency of 433 MHz a wavelength in water is .0774 meters or 3 inches. In this paper wavelength always refers to this quantity.

3. ANTENNA BACKGROUND

The antenna radiation pattern is the radiation intensity as a function of either azimuthal or elevation angle. An isotropic antenna would be one that radiated in all directions equally. An omnidirectional antenna is one that radiates uniformly in one plane [12]. The radiation resistance R_r is that part of the resistance seen at the input terminals caused by electromagnetic radiation from the antenna. The other part is caused by losses. An antenna with a large radiation resistance is more efficient, because the power radiated is larger than the power lost. The input impedance of an antenna is the impedance at its input terminals, both the real and imaginary part. The maximum power is delivered to the antenna when the antenna and transmitter are matched, that is the input impedance of the antenna equals the complex conjugate of the output impedance of the transmitter. The maximum power is delivered to a receiver when the receiver and antenna are matched [12]. Because of the difference in wavelength, the physical dimensions of an antenna in water would be about 1/9 of the dimensions of an equivalent antenna in air. Because of the difference in intrinsic impedance, the input impedance of an antenna in water would be about 1/9 of the input impedance of the equivalent antenna in air.

4. ANTENNA REQUIREMENTS

We have been exploring different antennas for use in the mussel-based underwater WSN depicted in Figure 1. An effective antenna for this application must meet a number of requirements. Primarily, the antenna must be small enough so that one can glue this to a mussel. Mussel sizes vary with age and species—we currently focus on mussels that are about 3 inches long and 2

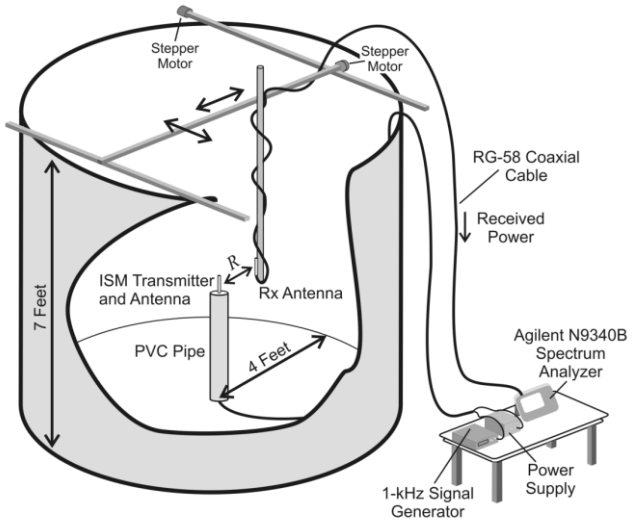

Figure 2. Experimental set up. The tank is filled with water and the stepper motor precisely controls the distance between the transmitter and the receiving antennas.

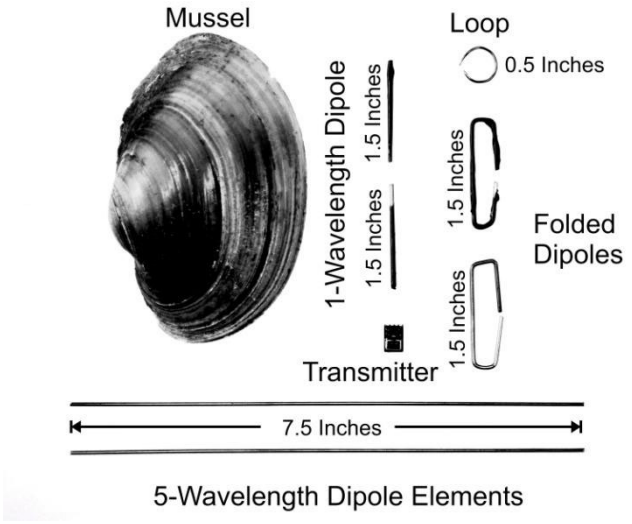

Figure 3. The antennas tested compared to the size of the mussel we would mount them on.

inches wide. One wants the antennas not much larger than 50% of these dimensions, namely 1.5 inches × 1 inch. We do not make assumptions regarding mussel orientation, so an isotropic antenna is desirable. Mussels may bury themselves in the mud layer in a river when seeking protection. Thus, the antenna must operate in river water, or partially- and even completely buried in sediment. These different environments have different conductivities and dielectric constants, and these impacts wavelengths of electromagnetic waves. Furthermore, the electrical conductivity in a river varies with time so that antenna radiates into a non-stationary propagation environment. This implies that a broadband antenna is preferable to a highly tuned, narrowband antenna. Also, as we outline above, river water presents a significantly-different environment to an antenna and attached radio than does the air. The water affects the radiation pattern and antenna impedance, and thus the overall efficiency of the transmitter. Still, our goal is to use very simple, inexpensive antennas, and avoid impedance matching networks. We want to identify antennas that will allow non-electrical engineering researchers to easily construct underwater biological sensor networks. Finally, antennas in water are prone to corrosion and fouling. An insulated antenna is preferred to one made of bare metal.

5. METHODOLOGY

We investigated the performance of three well-known antennas, namely the dipole, loop, and folded dipole as follows. We designed these antennas as if they would operate in air, but reduced the dimensions by 9 to account for the wavelength shortening that occurs in water. Figure 2 shows the experimental setup, which consists of a circular plastic tank 8 feet in diameter and 7 feet tall, filled with water ($\sigma \cong 0.05$ S/m). In any enclosed area reflections from sides and bottom can be a source of error. The amount of reflection can be minimized by the choice of tank material or by special coatings. Since electromagnetic waves attenuate as they travel through water, the ratio of reflected wave to transmitted wave is a maximum at the edge and a minimum at the center. Therefore the error in measurements made in the interior may be acceptable. This proved to be the case in our experiment.

A length of PVC pipe extends vertically from the center of the bottom of the tank. On top of this lower pipe, we placed a module containing a Radiotronix RCT-433-AS (B) transmitter sealed in epoxy. The transmitter has an output impedance of 50 ohms and contains a simple network to match antenna impedances close to 50 ohms to the transmitter. A computer-controlled *x-y* positioner is located on top of the tank. Another PCV pipe extends vertically down into the tank from the positioner. The experimental setup allows one to position the receiving antenna accurately (~ 2 mm) with excellent repeatability.

Attached to the upper pipe was a receiving antenna consisting of a small insulated dipole with a total length of 5/8 inch (0.2 λ). This receiving antenna was at the same depth as the transmitter. A cable leads from the receiving antenna to an Agilent N9340B spectrum analyzer. The antenna to be evaluated is attached to the transmitter and the positioner moves the receiving antenna in

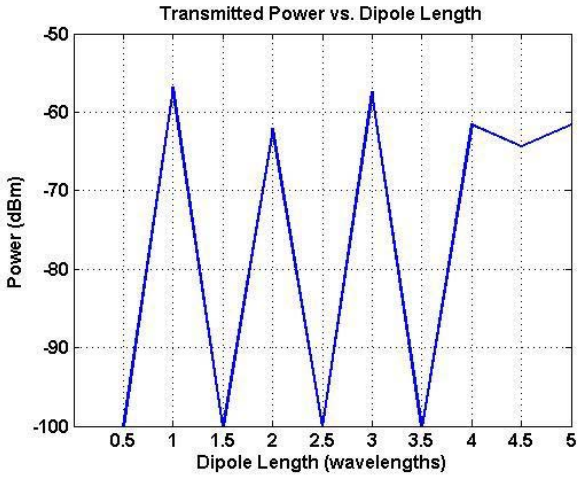

Figure 4. Transmitted power as a function of dipole length at maximum range (27 inches)

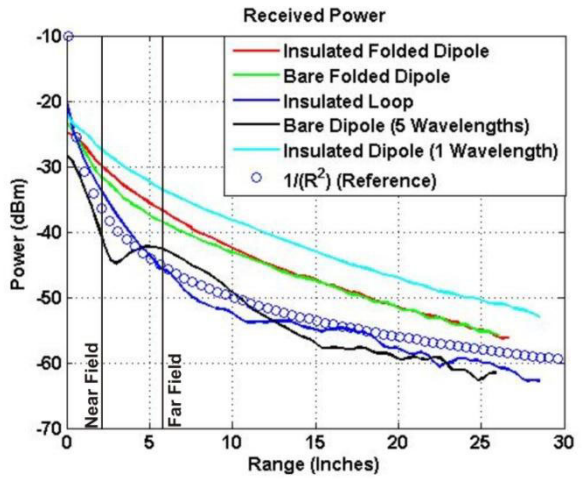

Figure 5. Received power vs. range for the candidate antennas

small increments. At each increment, we measured and recorded the received channel power. To reduce random noise, we configured the spectrum analyzer to average the power measurements.

6. ANTENNAS TESTED

Figure 3 shows the antennas we explored. Since dipole antennas are simple to construct, and widely-used, we started our investigation with dipole antennas as follows. We constructed a 5-wavelength (15 inches) antenna and measured the received power at a maximum separation of 27 inches. We reduced the dipole length in half-wavelength steps and measured the channel power at each step. Figure 4 summarizes the results and indicates that a 3-inch dipole radiates efficiently. Next, we made detailed power vs. range measurements for 3-inch dipole and 15-inch dipole antennas.

Another popular, compact antenna is a folded dipole, which is the next antenna that we explored. Loop antennas are another class of compact antennas, and we explored a half-wavelength (circumference) loop antenna. Additionally, we explored the effect of constructing antennas from bare vs. insulated copper.

7. RESULTS

Figure 5 summarizes the results for the different antennas. The near-field for the antennas about 2 inches, and the far field is about 6 inches, also indicated in the figure. For reference, we also show a $1/R^2$ response, which is what one would expect for the far-field power-distance in an unbounded, non-conducting medium.

8. DISCUSSION AND CONCLUSION

The insulated 1-wavelength dipole performed the best. Over the entire range of measurements, its received power was about 5 dB greater than any other antenna. Oscillations in the received power are evident when the range is about 17 inches or more. Both folded dipoles performed very well, with the insulated folded dipole performing a little better than the uninsulated folded dipole. As with the dipole, oscillations in the received power are evident close to the tank wall. These oscillations suggest reflections/multipath. Closer examination reveals that the maxima/minima are spaced 1.5 inches or $0.5\,\lambda$ apart, which supports the notion of reflections off the tank wall. For all dipoles the oscillations are less than 0.5 dB peak-to-peak, indicating that reflections are not a significant factor in the measurement region. In the very near field, the insulated loop performs better than any other antenna, but the received power falls off very rapidly. The power of the insulated loop shows significant variation at greater distances.

Our results show that a simple, insulated dipole outperforms the other candidate antennas, and meet the other important requirement, namely be small enough to be attached to a freshwater mussel. However, there are other factors which we have not yet explored. The close proximity of the mussel and the river bottom may affect transmitted power, as could interference by reflections from the water free surface. Finally, in the future we plan to measure the radiation patterns of the antennas to see which is most isotropic.

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