Surface Wave Based Underwater Radio Communication
Igor I. Smolyaninov, Quirino Balzano, Christopher C. Davis, and Dendy Young

Abstract—An underwater portable radio antenna operating in the 50 MHz band and efficient for launching surface electromagnetic waves at the seawater/air interface is presented. The antenna operation is based on the field enhancement at the antenna tip and on an impedance-matching antenna enclosure, which is filled with deionized water. This enclosure allows us to reduce antenna dimensions and improve the coupling of electromagnetic energy to the surrounding salt water medium. Since surface wave propagation length far exceeds the skin depth of conventional radio waves at the same frequency, this technique is useful for broadband underwater wireless communication over several meters’ distances.

Index Terms—Impedance matching, surface electromagnetic wave, underwater communication.

I. INTRODUCTION

It is very difficult to employ radio signals for long-distance undersea communication because they are rapidly attenuated in fresh, brackish, and salt water. Performance of conventional RF communication schemes in water is limited by the relatively small RF skin depth, which may be estimated as follows:

$$\delta = \sqrt{\frac{1}{\pi \mu_0 \sigma \nu}} \approx \frac{270 \text{ Hz}^{1/2} \text{ m}}{\sqrt{\nu}} \quad (1)$$

where $\sigma$ is the water conductivity and $\nu$ is the communication frequency [1]. This signal attenuation severely limits the ability to communicate over distance in water. For example, at $\nu = 50 \text{ MHz}$ the skin depth in seawater is about 3.8 cm, so conventional techniques of RF communication are impractical in salt water over useful distances.

However, efficient coupling to surface electromagnetic modes [2] (such as the surface electromagnetic wave at the seawater/air interface) may enable much longer communication distances. The penetration depth $L_z$ and the propagation distance $L_r$ of a surface wave are given by the following expressions:

$$L_z \approx \frac{\lambda_0}{4\pi \sqrt{\varepsilon''}} \quad (2)$$

and

$$L_r \approx \frac{\lambda_0 \varepsilon''}{\pi} \quad (3)$$

respectively [3], where $\varepsilon''$ is the imaginary part of the relative permittivity of seawater, and $\lambda_0$ is the free space wavelength. Thus, at 50 MHz, the signal propagation distance appears to be rather large ($L_r = 60 \text{ m}$), while (assuming operation down to −90 dB relative signal levels) the communication depth may reach several meters. This argument is illustrated in Fig. 1, which shows the RF field distribution in seawater produced by a point source located in the vicinity of the seawater/air interface. The

Fig. 1. Numerical simulations of RF field distribution in seawater (shown in logarithmic scale) produced by a 50 MHz point source located in the vicinity of the seawater/air interface performed using the COMSOL Multiphysics solver.

Manuscript received October 11, 2018; accepted November 5, 2018. Date of publication November 7, 2018; date of current version November 29, 2018. (Corresponding author: Igor I. Smolyaninov.)

I. I. Smolyaninov and D. Young are with the Saltena LLC, McLean, VA 22102-4903 USA (e-mail: igor.smolyaninov@saltena.com; dendy.young@saltena.com).

Q. Balzano and C. C. Davis are with the Department of Electrical and Computer Engineering, University of Maryland, College Park, MD 20742 USA (e-mail: qbalzano@umd.edu; davis@umd.edu).

Digital Object Identifier 10.1109/LAWP.2018.2880008
term “seawater” will be used throughout this letter to describe a water environment with approximately 3.5% salinity and a relative permittivity of $\varepsilon = 79 + 32i$ [4]. At some distance from a source, the field distribution is dominated by the surface electromagnetic wave, which enables RF communication from point A to point B, which would otherwise be impossible in the absence of the surface wave due to the skin effect in bulk seawater.

Below we will demonstrate that an underwater radio antenna operating in the 50 MHz band, suitable for efficient excitation of surface electromagnetic waves at the seawater/air interface, can be realized. Since surface wave propagation length far exceeds the skin depth of conventional radio waves at the same frequency, such an antenna may be useful for broad-band underwater wireless communication over several meters distances.

II. ANTENNA DESIGN AND DISCUSSION

There is a rather extensive literature on the propagation of radio waves in sea water [5] and on the performance of antennas in such environment. Siegel and King [6] demonstrated that practical size antennas can be modeled as electrically short dipoles and exhibit dipole behavior in sea water. Yoshida [7] points out that it is necessary to keep the entire communication system underwater to avoid above-water transmitter–receiver coupling. A detailed analysis of sea rough upper surface effects on radiated fields is presented in [8]. In this letter our antenna design followed the analysis developed in [9] to evaluate the RF fields radiated from a short dipole in a highly dissipative environment, human tissue. Abo-Seida et al. [8] shows a short dipole enclosed in an insulating layer to avoid the RF losses caused by the high E-fields at the tips of an antenna immersed in a highly dissipative medium.

In this letter, following the analysis in [9], a helical dipole resonant at 50 MHz, which is more efficient than a linear short of the same length, has been used as a radiating structure, enclosed by a substantial insulating layer of deionized water to minimize reactive near-field losses and to provide a minimal matching structure for wave propagation in sea water. A photograph of the 50 MHz underwater antennas optimized for surface electromagnetic wave excitation is shown in Fig. 2. The antenna operation is based on the field enhancement at the antenna tip and on the impedance-matching antenna enclosure, which is filled with deionized water. This enclosure allows us to reduce antenna dimensions by approximately a factor of 9 compared to free space dimensions, and to improve the coupling of electromagnetic energy to the surrounding seawater medium [10]. In addition, it considerably reduces the ohmic losses that would be caused by the immersion of the antenna in saline water.

The impedance-matching enclosure around the antenna uses an impedance-matching fluid. Deionized water can be such a fluid because it has about the same real part of relative permittivity as seawater and much smaller conductivity ($\varepsilon = 81 + 16.42i$ [4]). As illustrated in Fig. 3, laboratory testing of the deionized water based impedance-matching enclosure concept performed in brackish water (0.5% salinity) at 2.45 GHz. The transmitter–receiver set equipped with impedance-matching enclosures shows a $\sim$20 dB advantage compared to the same antennas directly immersed in brackish water. The comparative advantage grows quickly with increased salinity, since unenclosed operation of these antennas in seawater becomes impossible due to losses.

The radiating structure selected to maximize the electric field at its tip was a helical monopole (see Fig. 4). The length and the diameter of the helical antenna were selected for resonance configuration, the same antennas were enclosed in impedance-matching containers filled with deionized water. There were no air gaps between the antennas in either configuration. The transmitter–receiver set equipped with impedance-matching enclosures showed a $\sim$20 dB advantage compared to the same antennas directly immersed in brackish water. However, we also mention that other impedance-matching fluids and/or media may be engineered for the same purpose of drastically reducing the near-field antenna losses [10].
in deionized water at 50 MHz. The monopole helix, with a ground plane, resonant at 450 MHz was immersed in a water bath and trimmed for resonance at 50 MHz. The tuning was further refined by immersing the antennas in a gallon container of deionized water and using a network analyzer (see Figs. 5 and 6). In addition, the tapping point for a 50 Ω match to a feeding coaxial line was also determined by experimental tests using the setup shown in Fig. 5. The finalized helical monopole was 16 cm long with 0.7 cm diameter. The electric field at the antenna tip was further maximized by tip sharpening.

Two Yaesu submersible waterproof 5 W transceivers, model VX-8DR/DE, were used to test the antenna performance. The helix structure was fed with a coaxial line 11 cm long. One end of the helix was short circuited to the coaxial ground (also the ground of the transceiver), while the center conductor of the coax line was used to feed the metal helix at 11 turns away from the ground point. Fig. 4 shows the assembled helical monopole and transceiver (without the impedance-matching enclosure). The final tuning of the antenna was performed by maximizing the received signal at 0.5 m distance using the two identical structures shown in Fig. 2.

III. MEASURED RESULTS

The operational performance of the surface-wave antennas described above has been tested in an underwater, saline environment near Panama City, FL, USA (water salinity 2.8%–3.2% depending on time of the day). The operating frequency was 50 MHz. The seawater environment was large enough (water depth at least 3 m) that no significant boundary effects were present. The effects of boundaries were tested separately by dedicated measurement runs performed near the sea floor and near the water basin borders. These boundaries were determined to have no effect on the measurement results. All the tests were conducted with separate transmitting (TX) and receiving (RX) antennas and radio systems enclosed in watertight containers (see Fig. 2), which were handled by divers. The divers verified their depth using fixed vertical markers. The distance between divers was measured by using fixed horizontal markers. It was verified that the markers (made of buoys and ropes—see Fig. 7) located inside the seawater had no effect on signal propagation between the radios. Signal propagation data read from the LED indicator and the S-meter of the Yaesu radios were reported by the divers and recorded by test personnel located on a nearby vessel. A picture of the Panama City sea water test conditions is presented in Fig. 8 showing two divers and their surface buoys. The communication range tests were conducted using the following steps at each depth/distance combination.

1) Two divers holding the TX and RX units, respectively, positioned themselves in seawater at the depth/distance markers.
2) The first diver pushed the push to talk (PTT) button on the TX unit 10 times for 1 s with 1 s intervals.

3) The second diver observed and reported the green LED RF link indicator and the signal level meter of his RX unit and reported if the RF link between the units had been established at the given depth/distance combination.

The averaged measured values of link probability are plotted in Fig. 9. The skin depth at 50 MHz in seawater is 3.8 cm. It is shown near the bottom left corner of the plot for comparison.

Fig. 9. Contour plot of the link probability as a function of depth/distance combination measured in seawater. The sea floor in these experiments was located at 3 m depth. The skin depth in seawater at 50 MHz is shown to the scale for comparison.

2506 IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, VOL. 17, NO. 12, DECEMBER 2018

IV. CONCLUSION

Regardless of the relatively strong signal variations mentioned above, the antenna performance during the underwater tests generally matched theoretical expectations. According to the theoretical simulations presented in Fig. 1, propagation of radio waves beneath undulated sea water surface is dominated by surface electromagnetic waves, at large distances from the source. Experimental results plotted in Fig. 9 strongly support this theoretical prediction. These experimental and theoretical results are novel and important, since until now it was generally believed that broad-band radio communication through seawater is impossible over any practically meaningful distance. We expect that further optimization of the antenna parameters will result in approaching the theoretical performance depth/distance limits described by (2) and (3), which will enable novel capacity for wide bandwidth RF signal transmission through seawater, while reducing the power requirements, weight, and size of the TX and RX units.
REFERENCES

[1] D. K. Cheng, *Fundamentals of Engineering Electromagnetics*. London, U.K.: Pearson, 1992, ch. 8.

[2] A. V. Zayats, I. I. Smolyaninov, and A. Maradudin, "Nano-optics of surface plasmon-polaritons," *Phys. Rep.*, vol. 408, pp. 131–314, 2005.

[3] K. A. Michalski and J. R. Mosig, "The Sommerfeld half-space problem revisited: From radio frequencies and Zenneck waves to visible light and Fano modes," *J. Electromagn. Waves Appl.*, vol. 30, pp. 1–42, 2016.

[4] T. Meissner and F. J. Wentz, "The complex dielectric constant of pure and sea water from microwave satellite observations," *IEEE Trans. Geosci. Remote Sens.*, vol. 42, no. 9, pp. 1836–1849, Sep. 2004.

[5] R. K. Moore, "Radio communications in the sea," *IEEE Spectr.*, vol. 4, no. 11, pp. 42–51, Nov. 1967.

[6] M. Siegel and R. King, "Electromagnetic propagation between antennas submerged in the ocean," *IEEE Trans. Antennas Propag.*, vol. AP-21, no. 4, pp. 507–513, Jul. 1973.

[7] H. Yoshida, "Underwater electromagnetics and its application to unmanned underwater platforms," in *Proc. IEEE Int. Underwater Technol. Symp.*, Tokyo, Japan, 2013, pp. 1–5.

[8] O. M. Abo-Seida S. T. Bishay, and K. M. El-Morabie, "Far-field radiated from a vertical magnetic dipole in the sea with a rough upper surface," *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 8, pp. 2135–2142, Aug. 2006.

[9] Q. Balzano et al., "Field and temperature gradients from short conductors in a dissipative medium," *Int. J. Antennas Propag.*, vol. 2007, 2007, Art. no. 57670.

[10] I. I. Smolyaninov, "Communication and sensor techniques for underwater radio communication," U.S. Patent 20180198536, Jul. 12, 2018.