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Underwater electromagnetic communications using conduction – Channel characterization

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ABSTRACT

Wireless underwater transmission is considered using electric field generated by a pair of electrodes with opposite current and detected by two receiving electrodes. Experiments were conducted at frequencies between 100 kHz and 6.35 MHz, using orthogonal frequency division multiplexing (OFDM). Our lab tests were performed in a plastic tank filled with salt water, and our sea test at the ocean surface and at 5 m depth (boundary free). Magnitude and phase-delay of the channel transfer function were modeled based on inference from dipole radiation theory in conducting medium. An exponential attenuation model fitted to the lab measurements indicated inverse cubic range dependence (near-field compliant). A rational-polynomial model provided the best match for the recorded magnitude, especially at low frequencies. Based on the exponential attenuation model, we estimated that the capacity of this channel is on the order of 10 Mbps in the 100 kHz–6.35 MHz band when inside half a meter radius with 1 W of transmit power, suitable for contactless data collection by remotely operated vehicles from single or multiple nodes via spectrum sharing. Finally, estimation of the effect range uncertainty of ±0.5 m can have on the achievable data rates showed up to 30% performance downtrend for 1 m range.

1. Introduction

Applications of electromagnetic field in underwater communications are short range transmission (<100 m) and very short range (<1 m), very high speed, transmission. Although our research is mostly concerned with propagation channel modeling [1], this technology supports the vision of a subsea positioning system – a network of devices scattered across the seabed that is used to guide ROVs to data collection sites mounted on production assets. When the vehicle is within close proximity of a data collection port, as illustrated in Fig. 1, it can transfer information at tens or hundreds of Mbps.

Two technically feasible RF conduction based designs for voice communication underwater were reported in [2]; one for divers (150 m range with 6 W of power), and the other for manned submersibles (1 km range with 280 W of power). Center frequency reported in the paper was 1.2 kHz, with bandwidth 1.5 kHz.

In [3], based on sea water frequency response obtained by transmitting a 1 μs pulse, it was shown that RF conduction method can deliver information at 1 Mbps for binary system. Another article has been published recently about a high-speed underwater RF solution using conduction [4], where the highest data rate reported was 1 Mbps at ranges 0.5 m, 0.8 m and 1 m.

Kelley et al. [5] described an orthogonal frequency division multiplexing (OFDM) solution for underwater RF communication. They performed simulations using BPSK, QPSK and QAM16, using frequencies between 0 MHz and

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10 MHz. In addition, they simulated Alamouti space–time diversity and channel coding using rate 1/3 turbo codes. They assumed Ricean fading if there were line-of-sight component, while the path-loss models followed the work from [6]. The authors of [5] estimated through simulation that with 1 W of transmit power, a 1.14 Mbps RF data rate could be possible out to 60 m and 400 kbps out to 1 km in 10 MHz bandwidth.

Properties of underwater RF communication channel are discussed in a number publications related to underwater wireless sensor networks, such as [7,8]. Section 2 gives background on electromagnetic field in conducting media based on the electric dipole antenna model.

In Section 3 we describe the system components and the experiment. Like Kelley et al. [5], we chose OFDM as the transmission method. An advantage of OFDM over single-carrier schemes is its ability to cope with frequency-dependent channel attenuation without complex equalization filters. In this respect, underwater RF channel is similar to a copper wire channel because of its time-invariance and frequency-dependent attenuation profile.

Section 4 presents the channel frequency response models for magnitude and phase, derived from the experimental data based on the theory of electric dipole in a conducting medium. Using those models, in Section 5 we present a capacity analysis for this channel, and discuss the impact of range mismatch on the achievable rate. With an ad hoc sensor network in mind, this analysis is expected to provide insight into node spacing limitations. Depending on the bit rate constraints, we envision spectrum sharing between multiple nodes. For example, there could be an OFDM downlink, for functions such as handshaking, subcarrier assignment and channel sounding, while uplink could be multiple-access OFDM (OFDMA) where each transmit node would utilize a portion of available subcarriers assigned by the master node. Section 6 concludes the paper.

2. Propagation model

It is a well known concept that an RF conduction antenna can be analyzed as electric dipole in conducting medium if a solution to the Helmholtz equation is found by factoring conductivity in the complex-valued propagation constant that we will see below. The effects of underwater propagation and ohmic losses due to relatively high conductivity of seawater are taken into consideration by factoring the conductivity into the frequency dependent propagation constant. Here we focus on the segments of the theory of electric dipole in a conducting medium that are most relevant to our channel model formulation.

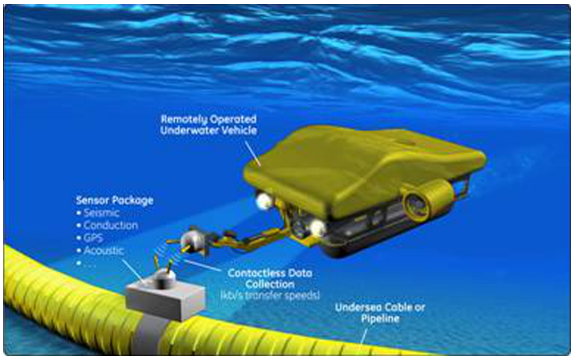

Fig. 1. ROV data upload.

There are three electromagnetic field components of a linear dipole antenna: radial and tangential electric fields E_r and E_θ, and magnetic field H_ϕ. The geometry of the antenna leads to coupling primarily of the E_θ component (the dipoles are parallel with centers in the same plane). It can be shown [9] that the tangential component of the electric field radiated by the infinitesimal dipole, at radial distance r from the source, is given by

$$E_\theta = j\eta\frac{kI_0 l\sin\theta}{4\pi r}\left(1+\frac{1}{jkr}-\frac{1}{(kr)^2}\right)e^{-jkr} \qquad (1)$$

where l is the antenna length and I_0 the current. The complex-values propagation constant k is a function of radial frequency ω, given by

$$k = \beta - j\alpha = \omega\sqrt{\mu\varepsilon\left(1-j\frac{\sigma}{\omega\varepsilon}\right)} \qquad (2)$$

where μ, ε, and σ are the permeability, permittivity and conductivity of the propagation medium, respectively. The characteristic impedance η of the medium is given by

$$\eta = \sqrt{\frac{\mu}{\varepsilon}\left(1-j\frac{\sigma}{\omega\varepsilon}\right)^{-1}} \qquad (3)$$

The electric field (1) can be expressed as

$$E_\theta = E(\omega, r)e^{-\alpha r}e^{-j(\beta r+\vartheta(\omega,r))}$$

For a given range $r, E(\omega, r)$ has rational polynomial form in terms of ω. The product βr represents the propagation delay of the electromagnetic wave, while $\beta r + \vartheta(\omega, r)$ is the phase of the electric field.

Frequency variation of the magnitude of tangential electric field component between 0 Hz and 6.5 MHz is

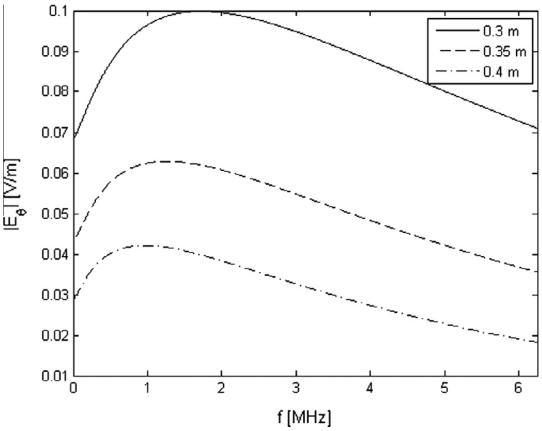

Fig. 2. Tangential electric field component magnitude as a function of frequency for several transmitter–receiver distances. $I_0 = 1$ A. Dipole length $l = 10$ cm.