Underwater Wireless Communication Using Coil-Based Magnetic Induction

Chaoxian Qi, Debing Wei, Miao Pan, Jiefu Chen
Department of Electrical and Computer Engineering
University of Houston
Houston, TX, USA
cqi4@uh.edu, dwei3@uh.edu, mpan2@uh.edu, jchen82@central.uh.edu

***Abstract*—A coil antenna-based magnetic induction (MI) scheme for subsea wireless communications is introduced. Magnetic induction (MI) is considered to be a good candidate to overcome the challenges posed by the harsh underwater environment. The designed MI communication system is implemented in hardware. Both numerical simulations and lab experiments are performed to demonstrate the effectiveness of the MI antenna.**

I. INTRODUCTION

Underwater wireless communication (UWC) techniques are playing an important role in the exploration of oceans and other aquatic environments. The need for UWCs has extended to broad applications, including off-shore oil exploration, pollution monitoring, collection of scientific data, as well as national security and defense. Thus, reliable and effective UWC techniques are imperative. A good review of the UWC techniques can be found in [1]. Unlike terrestrial wireless communications, the underwater channel poses serious challenges depending on the employed communications modalities (e.g. RF, optical or acoustic). These include, but are not limited to, ambient channel noise, severe attenuation, propagation delay, multipath, frequency dispersion and so forth [2].

In this paper, we proposed to apply the low-power coil antenna for magnetic induction (MI)-based wireless communication. The mathematical model of the MI channel is given. Both numerical simulation and lab experiments are performed and the experimental results indicate the coil antennas can be used in UWC applications without the aforementioned challenges.

II. THEORY

A. Coupling Coefficient Between Two Coils

Given two coils, one is the transmitter and the other is the receiver. If the transmitter is fixed and the receiver is moved away, the induced voltage in the receiver decreases due to less magnetic flux is linked with the receiver. Wei *et al.* [3] have already investigated the induced voltage on the receiver for different distances away from the transmitter using numerical simulations. In this work, we use the coupling coefficient K to quantify the coupling between the transmitter and the receiver, which is defined as

$$K = \frac{M}{\sqrt{L_1 L_2}}, \tag{1}$$

where M is the mutual inductance between two coils and L_1 and L_2 denote self-inductance, respectively. By assuming the transmitting coil and the receiving coil are identical, M and L_1, L_2 are given as [4],

$$M = \frac{N_2 \Phi}{I_0} = \frac{2\pi N_1 N_2 R E_\phi}{-j\omega I_0}, \tag{2a}$$

$$L = \mu_0 \mu_r N_1 N_2 R \left(\ln \frac{8R}{r_w} - 2 \right), \tag{2b}$$

where R is the coil radius, I_0 is the excitation current, N_1 and N_2 denotes the number of turns in transmitter and receiver, respectively. r_w is the wire thickness. E_ϕ is the electric field in the ϕ direction generated by the transmitter. E_ϕ is written as

$$E_\phi = \eta \frac{(\beta R_t)^2 I_0 \sin\theta}{4r} \left[1 + \frac{1}{j\beta r} \right] e^{-j\beta r}, \tag{3}$$

where β is the wavenumber, ω is the angular frequency, $\eta = \sqrt{\frac{\mu}{\epsilon_c}}$ is the wave impedance, μ is the medium permeability, and ϵ_c is the medium effective permittivity.

The commercial package COMSOL Multiphysics is used to simulate the coupling coefficient in inhomogeneous media. Fig. 1 shows the coupling coefficient varying with the distance between two coils both in the air and water with parameters listed in Table I. We observed the simulation results are consistent with analytic results. The coupling coefficient decreases faster in the water than it in the air due to higher attenuation. It is self-evident that the coupling coefficient decreases with the transmission distance.

B. MI Bandwidth

To determine the available bandwidth of an MI wireless communication system, the equivalent circuit model of MI channel is given. In this paper, we only talk about the series-resonant transmitter, as shown in Fig.2(a). The excitation voltage source U is in series with matched capacitor C_1 and

TABLE I
SIMULATION PARAMETERS.

I_0	N	R	r_w	coil conductivity σ
1 A	25	0.1 m	0.057 m	$1.5e^7$

978-1-7281-6670-4/20/$31.00 ©2020 IEEE

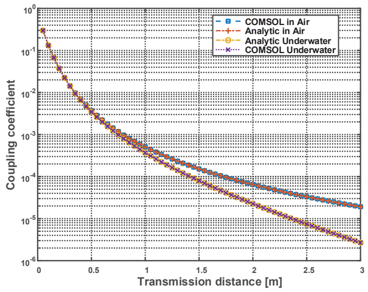
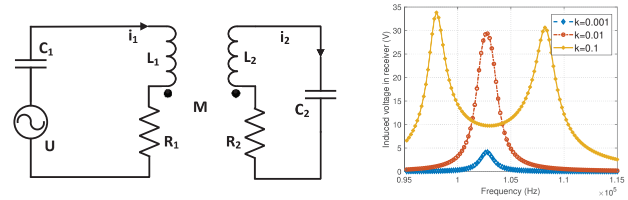


Fig. 1. The coupling coefficient varies with the transmission distance.



(a) Series-resonant transmitter circuit model.

(b) Frequency response of an MI wireless communication system

Fig. 2. MI channel characteristics.

self inductance and resistance of the coil, L_1 and R_1. The electric behavior is governed by the Kirchhoff's Law (KVL) as,

$$(j\omega L_1 + \frac{1}{j\omega C_1} + R_1)I_1 + j\omega M I_2 = U, \tag{4a}$$

$$j\omega M I_1 + (j\omega L_2 + \frac{1}{j\omega C_2} + R_2)I_2 = 0. \tag{4b}$$

The variation of the coupling coefficient will cause significant fluctuations to the received MI signal. By solving (4), we can characterize the MI channel in terms of the available bandwidth. The received MI signals under different coupling coefficients is shown in Fig. 2(b). We find the received signal is amplified by 6 times when the coupling coefficient K is increasing from 0.001 to 0.1. Also, 3 dB bandwidth is increased from 1 kHz to 7 kHz as K varies from 0.001 to 0.1.

III. EXPERIMENT

To evaluate the communication performance, we designed an underwater MI test-bed as shown in Fig. 3. Two coil antennas with radius $r = 10$ cm were submerged into a water tank with maximum distance of 32 inch. The detailed description of experiment setup is ignored due to length limitation. Some text messages modulated by 16QAM scheme with center frequency at 113kHz, which is the self-resonant frequency of the coil antenna, are transmitted by TX coil in Fig. 3. Then we gradually increase the symbol rate until the message cannot be demodulated correctly on the receiver side. This help us to calculate the maximum symbol rate. By applying the linear equalizer we can successfully demodulate the received signal with the symbol rate up to 6 ksps and 0.0137 bit error rate (BER). The results are shown in Fig. 4.

TABLE II
SIMULATION PARAMETERS.

L_1, L_2	C_1, C_2	r_1, r_2 @100 kHz	U
400 μH	6 nF	4Ω	1 V

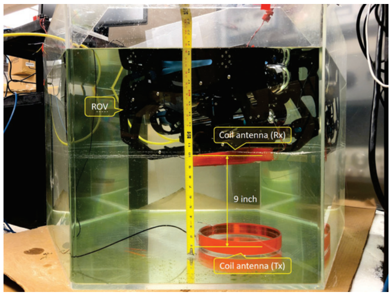


Fig. 3. Underwater MI test-bed

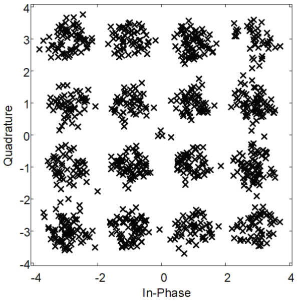


Fig. 4. QAM demodulation results with symbol rate of 6Ksps and 0.0137 BER , with equalization. The transmitted message is 'Hello world through underwater MI wireless communications!'

IV. CONCLUSION

In this paper, we mathematically characterized the MI channel. To evaluate the performance of the this UWC scheme, we proposed a soft defined MI communication test-bed system based on Matlab and USRP. The experimental results reveal that near field MI is a promising solution for low-power short range underwater wireless communications.

ACKNOWLEDGEMENT

This work was supported by the National Science Foundation under Grant No. CNS-1646607.

REFERENCES

[1] C. M. Gussen, P. S. Diniz, M. L. Campos, W. A. Martins, F. M. Costa, and J. N. Gois, "A survey of underwater wireless communication technologies," *J. Commun. Inf. Sys.*, vol. 31, no. 1, pp. 242–255, 2016.
[2] X. Zhang, J.-H. Cui, S. Das, M. Gerla, and M. Chitre, "Underwater wireless communications and networks: theory and application: part 2 [guest editorial]," *IEEE Communications Magazine*, vol. 54, no. 2, pp. 30–31, 2016.
[3] D. Wei, L. Yan, X. Li, J. Wang, J. Chen, M. Pan, and Y. R. Zheng, "Ferrite assisted geometry-conformal magnetic induction antenna and subsea communications for auvs," in *2018 IEEE Global Communications Conference (GLOBECOM)*. IEEE, 2018, pp. 1–6.
[4] C. R. Paul, *Inductance: loop and partial*. John Wiley & Sons, 2011.