Exploiting Magnetic Field Analysis to Characterize MI Wireless Communications in Subsea Environments

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***Abstract*—In this paper, we investigate the maximum transmission range and power efficiency of Magnetic Induction (MI) subsea wireless communication systems. We propose a new MI channel model based on maximum resonance voltage analysis. We prove that our channel model can maximize the system signal to noise ratio (SNR). Hence, the maximum transmission range of a MI wireless communication system can be determined accordingly. Furthermore, we quantify the eddy current loss of the MI coil antenna in seawater environments. The power consumption of a subsea MI wireless communication system is obtained by summing up the eddy current loss and ohmic loss. Finally, the relationship between the maximum transmission range and power consumption of a subsea MI wireless communication system is determined.**

I. Introduction

In underwater environments, transmission range and power efficiency are important to establish a reliable and sustainable wireless network which can enable efficient exploration and observation of underwater resources. Electromagnetic waves attenuate significantly in sea water medium [1], so that the traditional Radio Frequency (RF) wireless communications cannot be adopted for small size underwater devices. In contrast, the acoustic signal propagates well underwater [2], and acoustic wireless communications have been widely implemented for underwater wireless sensor networks in past decades. However, acoustic communications suffer from many disadvantages [3] (e.g., long propagation delay, low data rate, high error rate, etc.). The performance of acoustic wireless communications is still unjustifiable.

In recent years, Magnetic Induction (MI) has been considered a promising solution for wireless communications in underground and underwater environments [4]. For MI wireless communications, signals are transmitted by modulating the near magnetic field of a coil antenna. The operating frequency of MI is so low that the radiated energy can be neglected. Most of the energy is resonating between the coil inductance and resonant capacitor. As a result, high power efficiency can be achieved for a MI communication system. The propagation speed of a MI wave is above $10^5 m/s$ in sea water. Hence, the propagation delay of MI signals is much smaller than the acoustic wave. Even though the operating frequency of MI is much smaller than RF, it can still reach the MHz level. In comparison to acoustic wireless communications, a much higher data rate of MI can be expected. In addition, MI coils cost much less than the acoustic transducer. Therefore, it is very suitable for large-scale deployment of sustainable underwater networks.

MI channel modeling is essential to design a MI wireless communication system. Most research works on MI channel modeling are based on the circuit model shown in Fig. 1. The basic idea of this kind of channel modeling is to choose an appropriate load impedance i.e., $Z_L = (Z_{tr} + Z_{Lr} + R_r)^*$, such that the receiving power on Z_L can be maximized. Unfortunately, this circuit model cannot achieve the best MI performance, and the detailed analysis will be presented in Section II. Furthermore, the conductivity of seawater is widely neglected in these works, which makes the mutual inductance model not accurate in subsea environments. In [5], Guo et al. studied the mutual inductance and self inductance of 3D coil antennas, however, the ohmic loss and eddy current loss are not considered, which are extremely important for the transmission range and power consumption analysis.

This paper conducts the maximum transmission range and power consumption analysis of MI wireless communications, which are crucial for subsea applications. The transmission range is determined not only by the coil antenna parameters, such as coil radius and number of turns, but also by the system design. After accurate analysis of the mechanism of MI wireless communications, we point out that the circuit model that is commonly used in the current channel modeling literature [5]-[8] can be further improved. The concept of path loss in MI wireless communication is confusing since the power in MI system is not really lost but in fact not transmitted [6], [8]. Instead of following the path loss concept in RF communications, it would be better to directly analyze the induced voltage in the receiving coil. Hence, in this paper, the signal to noise ratio (SNR) is directly derived through field analysis. Based on SNR model, the maximum transmission ranges under different noise levels are derived. The optimal operating frequency in sea water medium is also revealed. Although the propagation of quasi-static electromagnetic fields can be treated as no power loss, the excitation current will cause ohmic loss in transmitting coils and the alternating electromagnetic fields will cause eddy current loss in subsea environments. Both of the ohmic loss and eddy current loss are

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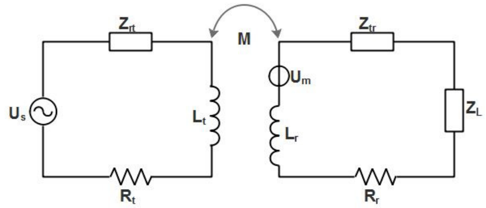

Fig. 1. Equivalent circuit model for MI communication

studied in this paper. Finally, the overall power consumption of an underwater wireless communication system is analyzed.

The rest of paper is organized as follows: Section II analyzes the drawbacks of the popular MI wireless channel model (we named it minimum path-loss model). Section III first develops the signal to noise ratio (we named it SNR model) of a MI wireless communication system through electromagnetic induction analysis. Then the transmission range limit of a underwater MI wireless communication system is discussed. Section IV investigates the power consumption of a MI wireless communication system. A mathematical model of eddy current loss in seawater circumstances is developed. Finally, we conclude the paper in Section V.

II. MI WIRELESS COMMUNICATION MECHANISM

In this section, the popular equivalent circuit model of MI wireless communication system is summarized. After detailed analysis, we show that this equivalent circuit model can be further improved by choosing a different load impedance Z_L.

A. Equivalent Circuit Model

The equivalent circuit model of a MI wireless communication system with two coupled coils is shown in Fig. 1, where M is the mutual inductance between two coils, L_t and L_r are the self inductance, R_t and R_r are the resistance of the coil. Z_{rt} and Z_{tr} are the reflected impedance that can be expressed as

$$Z_{rt} = \frac{\omega^2 M^2}{R_r + j\omega L_r + Z_L}, \tag{1a}$$

$$Z_{tr} = \frac{\omega^2 M^2}{R_t + j\omega L_t}, \tag{1b}$$

where $\omega = 2\pi f$ is the system angle frequency and f is the system operating frequency. The received power of the receiving coil which is consumed in the load resistance can be easily obtained by

$$P_r = Re\left\{\frac{Z_L \cdot U_m^2}{(Z_r + Z_{tr} + Z_L)^2}\right\}, \tag{2a}$$

$$Z_r = R_r + j\omega L_r, \tag{2b}$$

$$U_m = -j\omega M \frac{U_s}{R_t + j\omega L_t}. \tag{2c}$$

In most of the MI channel modeling papers [5]-[7], $Z_L = \overline{Z_r + Z_{tr}}$ is designed to be equal to the complex conjugate of the impedance of receiving coil so that the receiving power can be maximized. After the maximum receiving power is obtained, the so called path loss L_{EM} of MI channel [5], [6], [7] is defined as

$$L_{EM} = -10 \log \frac{P_r}{P_t}, \tag{3}$$

where $P_t = \frac{U_s^2}{R_t}$ represents the input power. We regard this MI channel model as the minimum path-loss model. Under this channel model, the received active power consumed by the load resistance can be maximized, but the reactive power and voltage magnitude of Z_L would be greatly reduced. Since the voltage signal of Z_L is what is needed for signal demodulation, the minimum path-loss model cannot achieve the best performance of MI wireless communication, which will be further explained in the next subsection.

B. Maximum Receiving Voltage Analysis

A coil antenna used for MI wireless communications can be regarded as a high-Q RLC tank resonator consisting of a resistor R, an inductor L, and a capacitor C. $Q = \frac{\omega L}{R}$ is the quality factor of the coil. The receiving loop is working under serial resonance conditions. So, the induced current I_r of receiving coil antenna is equal to

$$I_r = \frac{U_m}{R_r + Re\{Z_L + Z_{tr}\}}, \tag{4}$$

the load voltage is $U_L = I_r \cdot Z_L$. Considering the communication distance is much longer than the coil radius, the mutual inductance M between two coils would be very small, $Z_{tr} \ll Z_L$. For a high-Q coil, the resistance is much smaller than the inductance. Hence, the amplitude of load voltage can be approximated by

$$|U_L| \approx |U_m| \cdot \frac{\omega L_r}{R_r + Re\{Z_L\}}. \tag{5}$$

Eq. 5 shows that the maximum load voltage can be obtained by choosing $Re\{Z_L\} = 0$, which is twice larger than the load voltage of the minimum path-loss model, where $Re\{Z_L\} = R_r$. So,

$$|U_L| \approx |U_m| \cdot Q_r. \tag{6}$$

Here, Q_r is the quality factor of the receiving coil, which is determined by the coil parameters such as coil radius, number of turns, etc. U_m is the induced voltage in receiving coil, which is influenced not only by coil parameters but also by the exciting current of the transmitting coil, conductivity of propagation medium, and communication distance.

III. SNR MODEL OF MI WIRELESS CHANNEL

In this section, the induced voltage U_m as a function of transmission distance, coil parameters and conductivity of lossy medium will be derived based on field analysis. Then, the SNR and maximum transmission range limit are discussed considering different noise levels. Since it is well known that the best performance of MI can be achieved when the coils are co-axle aligned, we only need to consider the co-axle aligned MI wireless communication system for the maximum transmission range analysis. As proved in paper [5], the 3D tri-directional (TD) coil antenna is almost an isotropic radiator, so the conclusion in this section is also suitable for TD coil systems.

A. Induced Voltage U_m

The geometric relations between two co-axle aligned coils are shown in Fig. 2. Coil 1 with radius of r_1 has N_t turns and carries an alternating current I_t, which gives rise to an alternating magnetic field B. Some of the magnetic field will pass through coil 2 with radius of r_2 that has N_r turns. The alternating magnetic flux will induce an electromotive force (EMF) in coil 2, which is regarded as U_m in the previous section. The phase of U_m will be reversed if the phase of I_t is reversed. So the BPSK modulation and demodulation scheme can be well applied between these two coils for MI wireless communications. As long as U_m is detectable in coil 2, the information can be successfully transferred.

The magnetic field of a circular loop can be found in [10]. Since two coils are co-axially placed, we only need to consider the magnetic field component alone the axle direction. The magnetic field strength H_z and flux density B_z is given by

$$H_z = \frac{N_t I_t r_1^2}{2R^3}(1 + jkR)e^{-jkR}, \tag{7a}$$

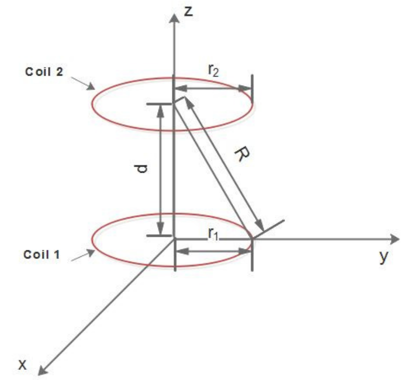

Fig. 2. Geometric information of two co-axle aligned coils

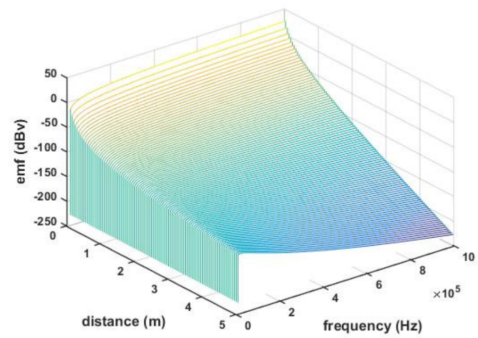

Fig. 3. EMF of receiving coil as a function of frequency and distance

$$B_z = \mu H_z, \tag{7b}$$

where $j = \sqrt{-1}$, $k = \omega\sqrt{\mu\epsilon}$ is the wavenumber. For lossy medium, $\epsilon = \epsilon_2 - j\frac{\sigma}{\omega}$, where ϵ_2 and σ are permittivity and electric conductivity of lossy medium, respectively. The EMF is proportional to the time rate of change of magnetic flux Φ, and the number of turns of receiving coil, i.e.,

$$U_m = -N_r \frac{d\Phi}{dt}. \tag{8}$$

The magnetic flux is determined by the magnetic field lines that passing through the area A of coil 2. For long distance communication, $d \gg r$, the magnetic flux density inside the receiving coil can be treated as B_z, So,

$$\frac{\partial \Phi}{\partial t} = \frac{\partial}{\partial t}\left(\vec{B_z} \cdot \vec{A}\right). \tag{9}$$

Hence, substituting Eq. 7 and Eq. 9 into Eq. 8, we have $U_m = N_r \omega \mu H_z \pi r_2^2$.

If two coils have the same parameters i.e., $N_t = N_r = N$ and $r_1 = r_2 = r$, then the amplitude of U_m can be approximated by

$$|U_m| \approx \frac{\mu\pi\omega I_t N^2 r^4}{2d^3} \cdot \sqrt{(1+\alpha)^2 + \alpha^2} \cdot e^{-\alpha d}. \tag{10}$$

Here, $\alpha = \sqrt{\mu\pi\sigma f}$. We regard it as the attenuation factor of the lossy medium.

B. Quality Factor Q

Q factor indicates the rate of energy loss to the stored energy of a resonator. High Q coils can achieve high power efficiency for a MI wireless communication system. High Q coil can also increase the sensitivity of receiving antenna because of the voltage magnification effect of a series resonance circuit.

The formula for finding Q uses the ratio of the inductive reactance to the total circuit resistance. The self inductance of a coil can be approximated by [11], where r_w is the wire radius.

$$L = N^2 \mu r \left(\ln \frac{8r}{r_w} - 2\right). \tag{11}$$

The total resistance R_{tot} of a coil consists of three parts, the ohmic resistance R_{ac}, the radiation resistance R_{rad}, and the equivalent eddy current loss resistance R_{med}. The ohmic resistance increases substantially with frequency, due to the skin effect and the proximity effect. The ohmic resistance accounting for skin effect is well studied in paper [9], which is given by

$$R_{ac\_skin} = \frac{\pi\mu f N r}{[\frac{r_w}{\delta} + e^{\frac{-r_w}{\delta}} - 1]}, \tag{12}$$

where $\delta = \frac{1}{\sqrt{\pi\mu_0\mu_r\sigma_w f}}$ is the skin depth, and σ_w is the conductivity of the wire material. The proximity effect will further increase the ohmic resistance. The added resistance due to the proximity effect for N-turn circular loop antenna can be found in [12]. Finally, the ohmic resistance of a coil can be approximated by

$$R_{ac} = R_{ac\_skin}(1 + k_p). \tag{13}$$

Here, k_p represents the coefficient of proximity effect and is determined by the wire spacing and number of turns. In this paper, we choose $k_p = 0.5$ for coil turns no more than 10.

The induction coil is capable of radiating electromagnetic waves into free space. The radiation power consumption is represented by radiation resistance R_{rad}. Based on [10], R_{rad} can be estimated by

$$R_{rad} \cong \left(\frac{8\mu_0\pi^5}{3c^3}\right) r^4 N^2 f^4, \tag{14}$$

where c is the speed of light, N is the number of turns, and r is the coil radius. For MI wireless communication systems, the operating frequency is around the MHz or KHz level. The radiation energy is really small and the equivalent radiation resistance is negligible when compared to the ohmic resistance.

When a coil is placed in a lossy medium environment such as seawater, the eddy current loops in the lossy medium will cause additional power loss. Considering the field intensity, the eddy current loss effect is much stronger in the transmitter coil than in the receiver coil. In this paper, we assume that $R_{med} = 0$ on receiver side due to the low-intensity fields. The eddy current loss on transmitter side will be studied in the next section.

In summary, the total resistance of receiving coil can be approximated by the ohmic resistance when accounting for skin effect and proximity effect. By substituting Eq. 11 and Eq. 13 into the definition of Q factor, we have,

$$\begin{aligned} Q_r &= \frac{\omega L}{R_{tot}} \\ &\approx \frac{2N\left(\ln\frac{8r}{r_w} - 2\right)\left(\frac{r_w}{\delta} + e^{\frac{-r_w}{\delta}} - 1\right)}{1 + k_p}. \end{aligned} \tag{15}$$

C. SNR Model and Maximum Communication Range

Based on previous analysis, we can see that if a transmitting coil is excited by an alternating current, the induced MI voltage signal can be calculated by Eq. 6. Then, the SNR of receiving coil can be expressed as

$$SNR = \frac{|U_L|^2}{50 \cdot P_{noise}}, \tag{16}$$

TABLE I
SIMULATION PARAMETERS

Name	Value	Description
μ	$4\pi \times 10^{-7}$ H/m	Permeabiliy
σ	4 S/m	Sea water conductivity
r	0.05 m	Radius of coil
N	10	Number of turns
I_t	1 A	Excitation current

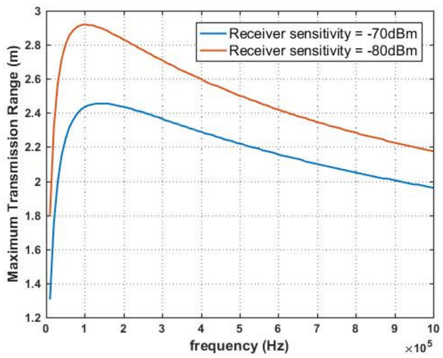

Fig. 4. Maximum transmission range of MI system with small coil, ($r = 5cm$, $N = 10$, $I_t = 1A$)

where P_{noise} is the overall noise power referenced relative to a 50-ohm impedance.

Considering a small coil antenna with radius $r = 0.05m$. The numerical parameters are provided in Table I. In Fig. 3, the amplitude of U_m as a function of distance and frequency is shown for sea water as predicted by Eq. 10. It's shown that as frequency increases, the attenuation of EMF becomes faster and faster. But the Q factor will become larger as frequency increases. Thus, it can be predicted that regarding a certain sensitivity level, there exists an optimal frequency that can achieve the maximum transmission range for MI wireless communications.

Consider the same actual sensitivity level of bluetooth, which is defined as the input level for which a raw bit error rate (BER) of 0.1% is met. The receiver sensitivity shall be below or equal to $-70dBm$ (standard sensitivity level), which means the minimum amplitude of receiving voltage should be larger than $99.985\mu V$. Let $U_L = 99.985\mu V$, the maximum communication range of MI wireless communication can be obtained from Eq. 6. For enhanced sensitivity level ($-80dBm$), $U_L \geq 31.618\mu V$. The results of maximum transmission range as a function of different frequency is shown in Fig. 4. We can see that the optimal frequency that can achieve the maximum communication range for subsea MI wireless communication is around 100kHz. Besides, 2 to 3 meter transmission range can be achieved with small coil antennas for MI wireless communication. The power consumption of such a compact communication system will be studied in the next section.

IV. Power efficiency of MI wireless communications

Power loss of a MI wireless communication system consists of three parts, the ohmic loss within coils, the electromagnetic radiation loss and eddy current loss due to the lossy medium. Each of these power loss can be represented by a specific resistance in the equivalent circuit. The ohmic resistance and radiation resistance have already been analyzed in details in the previous section. In this section, the eddy current loss is first investigated for transmitting coil.

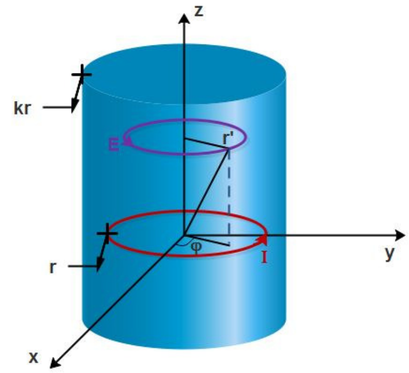

Fig. 5. The schematic diagram of eddy current loss

Then, the overall power consumption of a MI wireless communication system is formulated.

A. Eddy Current Loss

Due to the high electric conductivity of sea water, the alternating electric fields can cause eddy current in sea water. The eddy current loss can be calculated by a volume integral of the product of sea water conductivity and the square of electric field amplitude.

$$P_{eddy} = \int\int\int \sigma \left|E\right|^2 dv. \tag{17}$$

In order to derive the formula of eddy current loss, the following assumptions are made in this paper. 1) Most of the eddy current loss is within the area of cylinder shape with the radius of kr as shown in Fig. 5, where r is the radius of transmitting coil and k is a constant number. 2) The flux density within this cylinder shape is determined only by the Z coordinate. Therefore, the eddy current loss can be estimated by

$$P_{eddy} \approx \sigma \int_0^{kr} \int_0^{2\pi} \int_{-\infty}^{\infty} \left|E\right|^2 r' dr' d\varphi dz. \tag{18}$$

By the Faraday's law of induction, we can get the expression of electric fields, i.e.,

$$\begin{aligned} &\oint E \cdot dl = -\frac{\mathrm{d}}{\mathrm{dt}} \iint B \cdot dS \\ &\Rightarrow E \cdot 2\pi r' = \mu\omega H_z \cdot \pi r'^2 \\ &\Rightarrow E = \frac{\mu\omega H_z r'}{2}. \end{aligned} \tag{19}$$

Substituting Eq. 7 into Eq. 19, we get

$$E(r', z) = \gamma \cdot \frac{r'}{R^3} \cdot (1 + R\alpha + jR\alpha)\, e^{-R\alpha} e^{jR\alpha}, \tag{20}$$

where $\gamma = \mu\omega N I r^2/4$, $\alpha = \sqrt{\mu\pi\sigma f}$, and $R = \sqrt{r^2 + z^2}$. Combining Eq. 18 and Eq. 20, we may write

$$P_{eddy} = 4\pi\sigma \int_0^{\infty} \int_0^{kr} \left(\frac{\gamma^2 r'^3}{R^6} + \frac{2\gamma^2 \alpha r'^3}{R^5} + \frac{2\gamma^2 \alpha^2 r'^3}{R^4} \right) e^{-2R\alpha} dr' dz. \tag{21}$$

Since that $\frac{e^{-2R\alpha}}{R^{4,5,6}} \cong \frac{1}{R^{4,5,6}}$, the exponential part of (24) can be ignored. Then, after integral, we have the following formula.

$$P_{eddy} \cong \pi\sigma\gamma^2 (kr)^4 \left(\frac{3\pi}{16r^5} + \frac{4\alpha}{3r^4} + \frac{\pi\alpha^2}{2r^3} \right). \tag{22}$$

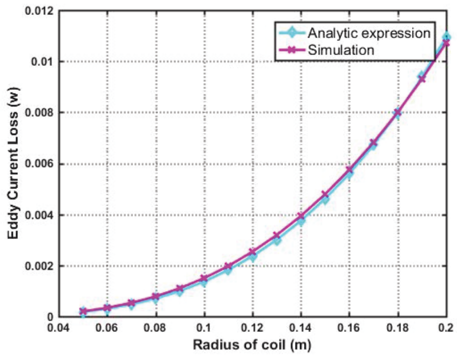

Fig. 6. Simulation and Numerical results of eddy current loss in sea water, $f = 100$kHz

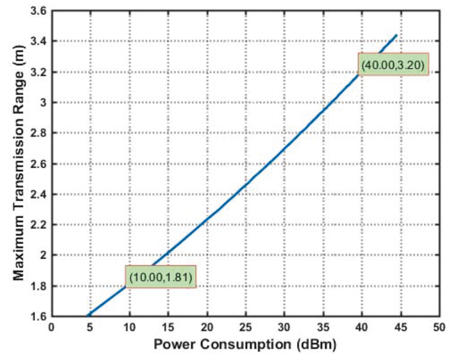

Fig. 7. The relations between power loss and transmission range, $r = 5cm$, $N = 10$, $f = 100$kHz

Considering that $r \ll 1m$, Eq. 22 can be further simplified as

$$P_{eddy} \approx k' \cdot \sigma \left(\mu\pi\omega NI\right)^2 r^3. \tag{23}$$

The coefficient k' can be obtained by the simulation. The model of a coil antenna that in subsea environments was built in Comsol Multiphysics and the results of eddy current loss are shown in Fig. 6. If we choose $k' = \frac{1}{18}$, the numerical result is almost consistent with the simulation result. Hence, this eddy current loss model is supposed to be accurate enough for MI wireless coil antenna design and analysis. The equivalent eddy current loss resistance of transmitting coil can be modeled by

$$R_{med} \approx \frac{\sigma \left(\mu\pi\omega N\right)^2 r^3}{18}. \tag{24}$$

B. Overall Power Consumptions

The overall power consumption of a coil can be calculated by $I^2(R_{ac}+R_{rad}+R_{med})$. For the transmitter, I represents the exciting current I_t, and for the receiver, I represents the induced current I_r. Because I_r is much smaller than I_t, the power consumption of receiving coil can be ignored for long distance MI wireless communications. Based on previous analysis, the radiation power loss can also be ignored. So the overall system power consumption can be estimated by

$$\begin{aligned} P_{loss} &\approx I_t^2 \left(R_{ac} + R_{med}\right) \\ &= I_t^2 \left[\frac{\pi\mu f N r \left(1 + k_p\right)}{\frac{r_w}{\delta} + e^{\frac{-r_w}{\delta}} - 1} + \frac{\sigma \left(\mu\pi\omega N\right)^2 r^3}{18} \right]. \end{aligned} \tag{25}$$

The relationship between power loss and transmission range for a specific coil antenna is shown in Fig. 7, in terms of the standard receiver sensitivity level that $U_L = 99.985\mu V$. It demonstrates that high power efficiency can be achieved for MI wireless communications. Thus, we can claim that 10dBm power consumption can achieve 1.8m transmission range for a small coil antenna with radius of 5cm. Fig. 7 also indicates that although the transmission range can be extended by increasing the exciting current, the power loss would increase much faster. For example, the power consumption would increase from 10dBm to 40dBm, if we want to extend the maximum transmission range from 1.8m to 3.2m by increasing the exciting current in the transmitter coil.

V. Conclusion

In this paper, the mathematical model of maximum transmission range and power efficiency are developed for subsea MI wireless communications, which is critical for its subsea applications such as the deployment of large scale, sustainable, MI based underwater sensor networks. By maximizing the resonance voltage of the receiving circuit, the channel model in this paper can notably enhance the SNR when compared to the existing one, which maximizes the receiving active power. Considering the same sensitivity level of Bluetooth communications, the maximum transmission ranges under different operation frequencies are plot out and the optimal frequency is derived for subsea MI wireless communications. Moreover, an approximation model of eddy current loss for sea water is presented, and the overall power consumption of a MI wireless communication system is derived. We found that despite the fast attenuation of magnetic fields, a relative good transmission range (few meters) can still be achieved by small power consumptions.

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