Network coverage using MI waves for underwater wireless sensor network in shadowing environment

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Abstract
In high permittivity media, such as underground, underwater, and biological tissues the electromagnetic (EM) wave fails to provide reliable communication due to high path loss. On the other hand, magnetic induction (MI) waves have the permeability similar to air in high permittivity medium. Unlike EM wave, in MI-based communication the effect of shadow fading on the obtainable transmission distance is not much pronounced. However, it may not be realistic to ignore the fading effect at higher frequencies considering a constant path loss while designing the link model. A channel model for underwater MI communication is proposed in this research work. The proposed channel considers the fading effect due to presence of large obstacles such as large underwater structures or seamounts, and old sunken ship on the coverage performance of an underwater wireless sensor network (UWSN).

1 | INTRODUCTION

With the recent advancement in communication techniques, wireless sensor networks (WSNs) have found tremendous applications in underwater environment for example, underwater autonomous vehicles (AUVs), aquatic life and underwater structures monitoring, autonomous robots and so forth. Unlike terrestrial WSNs, the transmission medium in underwater sensor networks (UWSNs) is water, where traditional techniques failed to produced the desired output. The conventional underwater communication relies on electromagnetic (EM), acoustic or optical wave propagation. The acoustic wave fails to provide reliable communication in the underwater environment due to long propagation latency, refraction and reflection, high bit error rate, multi path fading and low bandwidth. Optical wave communication such as narrow laser beam requires point to point (P2P) and line of sight (LOS) communication between the underwater AUVs. This is difficult to maintain the P2P and LOS communication due to highly mobile vehicles and water currents. Therefore, the two most commonly used modes of wireless communication are EM wave and magnetic induction (MI) wave communication. Among these two media, the latter one has promising characteristics, for example, negligible propagation delay, predictable and constant channel behaviour, sufficiently long communication range with wide bandwidth [1].

Recently, MI-based wireless communication with inductive sensor nodes has attracted a lot of attention. The literature shows significant progress in the field of underground wireless sensor networks [2–5]. However, it is still being explored enough in case of underwater wireless communication on consideration of different aspects. Akyildiz et al. [1] provided a thorough survey about the enormous applications as well as challenges of MI wave in underwater environment. Another survey paper [6] provides a deep analysis of several existing research on underwater MI communication. A detailed survey about the routing protocols for underwater communication using EM, acoustic, and optical waves can be found in [7] though the MI media has not been considered. The author in [8], has provided an analytical model for MI underwater communication using coil antenna. Furthermore, a comparative study of propagation characteristic using EM wave and acoustic wave with MI has been mentioned. It is observed that for MI waveguide system the transmission range has improved dramatically as compared to the ordinary MI and conventional EM wave media. The author has adopted the similar system model as discussed in [2], in which ordinary MI and MI waveguide techniques are used for underground communication. Improving transmission range using MI waveguide technique is also discussed by several authors in [9–11], and [12] for both underground and underwater MI communication. In [13], the first time authors have theoretically modelled the

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3D underwater network topologies for both shallow and deep water for large area underwater networks. In [14] authors have proposed a frequency selective WSNs for MI communication in complex environment such as underground and underwater environment. Further in [15] the authors have developed a location-based algorithm for wireless networks where the presence of many conductive objects have been taken into account. They have utilized the MI coils as radar to detect the induced eddy current generated on the conductive objects and thus locating the position of the coils and also the conductive objects as well. By this environment-aware information a localization algorithm has been developed which offers a significantly better localization accuracy than other existing algorithms for complex real environment. Authors in [16], have studied the MI communication in all types of underwater environment including the shallow water by considering the effect of lateral and reflected waves. Moreover, they have proposed a tri-directional transceiver coil antenna for establishing omnidirectional links in dynamic underwater environment. Till now, the influence of different parameters like frequency, number of turns and radius of the coil antennas, water salinity, and depth of the deployed sensors from air-water surface has been investigated for computing the overall path loss in the underwater medium. This path loss on the other hand determines the attainable transmission distance (i.e. the distance between the transmitter and receiver coil antennas). Another important aspect which has a significant impact on the attainable transmission distance is not explored enough that is, the attenuation due to the presence of shadow zones. It is found that most of the studies on UWSNs have ignored the effect of shadow fading due to its moderate effect on MI wave than on EM wave. However, for realistic link design and analysis, it is not useful to consider a uniform path loss at different underwater environment by ignoring the fading effects. The coverage performance of a WSN is directly proportional to the sensing range of the sensors which on the other hand largely depends on the overall path loss.

In the current scenario, it becomes necessary to investigate the techniques for reliable communication for undisturbed exploration and exploitation of underwater resources. The achievable coverage performance of an UWSN has not been explored enough under the influence of fading channel considering MI communication techniques.

In this motif, this proposed research work investigates the effect of fading on the overall path loss in UWSNs using MI wave as the communicating media. Furthermore, the coverage provided by the deployed sensor network based on received signal strength has been numerically computed. It is also observed that the influence of fading due to the presence of shadow zones on estimating the overall coverage provided by the inductive sensor nodes is more pronounced in case of conductive sea water. This study represents that for maintaining the desired coverage even with increasing number of induction coil sensor nodes is difficult in sea water medium.

This article is organized as follows: In Section 2, the system and channel model considered for our analysis is presented. Section 3 discusses the numerical and analytical results. Finally, Section 4 concludes the paper.

2 | SYSTEM MODEL

In a typical sensor network, the sensing characteristics of a sensor usually depends on the signal propagation mechanism. The received power at a sensor is a function of distance between the transmitter and receiver sensors, the propagation path loss, and the fading losses. The power received at rs distance from the desired sensor considering fading environment, is given in [17] as

\[ P_{\text{rcv}}(r) = P_t - L(r_0) - 10\eta \log(r_s/r_0) + \chi_{\sigma} \]  

where \( P_t \) denotes the common transmission power of the sensors, \( \eta \) is the path loss exponent which signifies the transmit power decay, \( r_0 \) is the reference distance at which the average propagation loss is \( L(r_0) \), \( \chi_{\sigma} \) is the Gaussian random variable (RV) with mean \( \mu = 0 \) and standard deviation \( \sigma_{\chi} \), representing the shadowing effects on the propagation path. In case of underwater communication, the received power depends also on the conductivity of the water. Therefore, it is evident from the above fact that the sensing signal is non-uniform in all directions unlike the deterministic Boolean sensing model [18, 19]. The signal from a sensor suffers from path loss and shadowing losses from the propagation environment. Equation (1) can be rewritten as

\[ P_{\text{rcv}}(r_s) = P_t - P_{\text{lossEM}} + \chi_{\sigma} \]  

where

\[ P_{\text{lossEM}} = L(r_0) - 10\eta \log(r_s/r_0) \]  

The work discussed in [17], models the received power considering propagation loss and fading losses using EM wave as the propagating signal. The author also stated that an appropriately chosen variance \((\sigma_{\chi}^2)\) can formulate the value of \(\chi_{\sigma}\), depicting the fading effects due to shadow zone for different types of sensing signals and in different propagation medium.

Equation (3) represents the path loss using EM wave as the propagating signal. However, the propagation media in underwater WSNs is different from the terrestrial one. In this work, MI wave is considered as the communicating media due to its enormous advantages over acoustic, EM, and optical wave in underwater communication. Therefore, the path loss will also be different from the above water environment. Furthermore, the permeability of MI wave is similar to air in the high permittivity material which results in moderate path loss in comparison to that in air [20].

In the proposed work, it is considered that all the inductive coil sensors are homogenous in characteristics (i.e. equal coil
resistance and inductance of the transceiver coils). Figure 1 shows a transmitter and a receiver coil antenna working in the near field region by coupling for communication in underwater environment. The distance between the transmitter and receiver coil antenna is assumed to be $r_s$. A time varying magnetic flux in the transmitter coil induces a voltage in the receiver coil by linking through the mutual inductance ($M$). The non-radiative near magnetic field (H-field) distribution is illustrated in the figure. The path loss for MI wave in underwater environment is given in [8] as

$$P_{\text{loss}} = -10 \log \frac{R_{\text{i}} \omega^2 M^2}{R_{\text{TX}} (R_{\text{i}} + R_{\text{RX}})^2 + R_{\text{TX}} (X_{\text{i}} + \omega L_{\text{RX}})^2}$$  \hspace{1cm} (4)$$

However, author has not considered the effect of fading losses while investigating the overall path loss. The overall path loss includes the additional effect of fading. As a result, Equation (4) can be written as

$$P_{\text{loss}} = -10 \log \frac{R_{\text{i}} \omega^2 M^2}{R_{\text{TX}} (R_{\text{i}} + R_{\text{RX}})^2 + R_{\text{TX}} (X_{\text{i}} + \omega L_{\text{RX}})^2 + \chi_{\sigma_r}}$$ \hspace{1cm} (5)$$

where $R_{\text{i}}$ and $X_{\text{i}}$ are the real and imaginary part of the load impedance, $R_{\text{TX}}$ and $R_{\text{RX}}$ are coil resistances in Ohms, and $L_{\text{TX}}$ and $L_{\text{RX}}$ are the self-inductance of the transmitter and receiver coil antennas in Henry, respectively. $M$ represents the mutual inductance between the two coil antennas and is expressed in Equation (6), $\omega = 2\pi f$ and $f$ is the operating frequency. For maximum power transmission $Z_1$ should be matched with the output impedance of the receiver coil.

The mutual inductance between two coils can be expressed as

$$M = \frac{\mu N_{\text{TX}} \alpha_{\text{TX}}^2 N_{\text{RX}} \alpha_{\text{RX}}^2 \pi}{2 \sqrt{(\alpha_{\text{TX}}^2 + \alpha_{\text{RX}}^2)}^3}$$ \hspace{1cm} (6)$$

where $\mu = \mu_0 \mu_i$ is the magnetic permeability, $\mu_0 = 4\pi \times 10^{-7}$ H/m is the magnetic constant, and $\mu_i = 1$ is the relative permeability of water. $r$ is the distance between the transmitter and receiver coil antennas (from the centre of the coil in the x direction) that is $r = (2\alpha + r_s)$. The self-inductance and resistance of the solenoid coil antenna can be calculated as

$$L = \frac{\mu N^2 A}{l}, \quad R = \frac{2\pi \rho N}{A}$$  \hspace{1cm} (7)$$

where $l$ is the length of the solenoid, $A = \pi(d/2)^2$ is the cross-sectional area of the wire and $d$ is diameter of the copper wire, $\rho$ is electrical conductivity of the copper wire. It is assumed that both the transmitter and receiver coil antennas are of same configurations that is $N = N_{\text{TX}} = N_{\text{RX}}$ and $\alpha = \alpha_{\text{TX}} = \alpha_{\text{RX}}$. From Equations (6) and (7), it can be concluded that the path loss in MI for underwater communication primarily depends on the number of turns $N$, the coil radius of both the transmitter and receiver coil antennas $\alpha_{\text{TX}}$ and $\alpha_{\text{RX}}$ respectively, distance between the transceiver coils $r_s$, and the operating frequency. In this work, it is assumed that the sensor nodes with induction coil antenna are randomly deployed according to homogeneous Poisson point process (PPP). The deployment of induction sensors may act as a discontinuous waveguide and will create a new form of propagating wave called magnetic wave [2], resulting in a longer transmission range. For modelling of the shadow fading channel model using MI as the communicating media, an infinite water environment is considered where no boundary exists. The effect of lateral wave on MI path loss is not considered [16].

Now, as per the sensing characteristic of the network is concerned, the received signal can only be successfully detected at the receiver sensor if the signal strength $P_{\text{rec}}$ exceeded the predefined threshold ($P_{\text{thres}}$). Therefore, the successful detection probability at distance $r_s$ can be expressed as

$$P_{\text{det}}(r_s) = P(P_{\text{rec}}(r) > P_{\text{thres}})$$ \hspace{1cm} (8)$$

Since $\chi_{\sigma_r}$ is a lognormal RV with a Gaussian distribution of mean $m_r$ and variance $\sigma_r^2$. Therefore, Equation (8) can be represented as

$$P_{\text{det}}(r_s) = Q\left(\frac{P_{\text{thres}} - m_r}{\sigma_r}\right)$$ \hspace{1cm} (9)$$

where $m_r$ is the mean received signal power and can be expressed as $m_r = P_s - P_{\text{loss}}$ with variance $\sigma_r^2$. Substituting $m_r$ in Equation (9), the expression for detection probability is obtained as

$$P_{\text{det}}(r_s) = Q\left(\frac{P_{\text{thres}} - (P_s - P_{\text{loss}})}{\sigma_r}\right)$$ \hspace{1cm} (10)$$

Here, $Q(x)$ can be expressed in terms of complementary error function ($\text{erfc}$) as $Q(x) = \frac{1}{2} \text{erfc} \left( \frac{x}{\sqrt{2}} \right)$. Now, substituting the expression of path loss for MI into
Equation (10), the detection probability of underwater sensor network can be deduced as

\[
P_{\text{det}}(r_s) = Q\left(\frac{P_{\text{dres}} - \left(P_t + 10 \log \frac{R_{L\omega^2M^2}}{R_{TX}(R_L + R_{RX})^2 + R_{TX}(X_L + \omega L_{RX})^2}}\right)}{\sigma_t}\right)
\]

(11)

In 3D underwater environment, the sensing region of a sensor can be assumed as a sphere of radius \(r_s\). Hence, the sensing coverage of each individual sensor can be considered as \(4\pi r_s^3/3\). The probability that a sensor is located in the annulus at a distance \(r_s\) from the target receiver sensor is \(4\pi r_s^2 dr_s/A'\), where \(A'\) is the area of the region of interest and \(dr_s(0 < dr_s \ll 1)\) is width of the annular region. Therefore, the probability of successful detection of the sensing signal by the receiver sensor can be expressed as

\[
P_{\text{det}} = \int_{r_s=0}^{R_{\text{max}}} P_{\text{det}}(r_s) \times \frac{4\pi r_s^2}{A'} dr_s
\]

(12)

Here \(R_{\text{max}}\) denotes the maximum practicable sensing radius of a node in the underwater environment. Substituting Equation (10) into Equation (12), the successful detection probability is obtained as

\[
P_{\text{det}} = 4\pi \int_{r_s=0}^{R_{\text{max}}} Q\left(P_{\text{dres}} - \left(P_t - P_{\text{loss}}\right)\right) \times \frac{\sigma_t}{\sigma_t} r_s^2 dr_s
\]

(13)

From the definition of sensing coverage, the coverage probability of a deployed sensor network can be represented as

\[
P_c = (1 - \exp^{-N_i P_{\text{det}}})
\]

(14)

where, \(N_i\) is the total number of deployed inductive sensor nodes. Therefore, the coverage probability of the deployed sensor network in underwater medium can be expressed as Equation (15).

It is observed from Equation (15) that the sensing coverage acquired by the sensor networks in underwater environment not only depends on the number of deployed sensors, sensing sensitivity, and distance between the sensors that is the distance between transmitting coil antenna and the receiver coil antenna but also on the coil parameters (e.g. coil radius, number of turns), the operating frequency and on the presence of huge obstacles in underwater environment which creates shadow zones. Moreover, the sensing coverage further degrades in salty water that is sea water due to induced eddy current produced by the salinity of the sea water. The attenuation in sea water due to induced eddy current is \(a' = 1/\delta = \sqrt{\pi f \mu \sigma}\), where \(\delta\) is the skin depth, \(\sigma\) is electrical conductivity of sea water. Therefore, in sea water, the total path loss is path loss in fresh water plus the attenuation due to eddy current losses and can be expressed as in [8] as

\[
P_{\text{loss}\text{sw}} = P_{\text{loss}} + P_{\text{loss} \delta \text{att}}
\]

(16)

Substituting the expression of \(P_{\text{loss}}\) into Equation (16) the total path loss in sea water can be given as

\[
P_{\text{loss}\text{sw}} = -10 \log \frac{R_{L\omega^2M^2}}{R_{TX}(R_L + R_{RX})^2 + R_{TX}(X_L + \omega L_{RX})^2} + 20 \log(e^{a' t}) + \chi \sigma_t
\]

(17)

Thus the coverage probability of the deployed sensor network in sea water further degrades in comparison to the freshwater environment. The coverage in sea water can be obtained by substituting the expression of \(P_{\text{loss}\text{sw}}\) in Equations (13) and (14) as

\[
P_c = \left(1 - \exp^{-\frac{N_i}{2\pi} \int_{r_s=0}^{R_{\text{max}}} Q\left(t_{\text{dres}} - \left(P_t - P_{\text{loss}\text{sw}}\right)\right) r_s^2 dr_s}\right)
\]

(18)

3 | NUMERICAL RESULTS

In this section, the effect of various parameters on coverage provided by the deployed sensor network in underwater...
TABLE 1 Values of different parameter used for analysis

| Parameter                          | Value                                   |
|-----------------------------------|-----------------------------------------|
| Radius of transmitter coil $\alpha$ | 1 m                                     |
| Radius of receiver coil $\alpha$   | 1 m                                     |
| Number of turns of transmitter coil | 1000                                    |
| Number of turns of receiver coil   | 1000                                    |
| Length of the solenoid            | 6 m                                     |
| Radius of the copper wire         | 0.725 mm                                |
| Electrical conductivity of the copper wire | 0.01724 $\Omega$ mm$^2$/m               |

Figure 2 Path loss with the variation of frequency $(f)$ and number of turns $(N)$ for $\sigma_i = 4$ dB and coil radius $r = 1$ m. The environment has been investigated. Simulation tool used for carrying out the analysis is MATLAB. The maximum practicable sensing radius is considered as $R_{\text{max}} = 10$ m and the number of sensor nodes varies from 0 to 2000. The parameter values used are mentioned in Table 1.

Figure 2 shows the variation of path loss for MI wave as a function of frequency and number of turns in underwater media. Here the path loss includes the additional effect of fading due to shadow zones in underwater environment. The plots are shown for fresh water and sea water. It is observed that the path loss decreases with increasing frequency. However, the decrease in path loss due to the increase in number of turns in coil antenna is significant. Moreover, the losses further increases in sea water. By comparing with the results in [8] it is observed that for $f = 1000$ Hz and number of turns $N = 500$, the path loss in sea water obtained considering fading is 40.32% higher as compared to path loss obtained without fading.

The variation of path loss with frequency and coil radius is depicted in Figure 3. It is observed that path loss decreases with increasing coil radius and frequency. For larger coil radius, the impact of frequency on path loss becomes less significant. It is also observed that the loss in sea water is higher as compared to fresh water. The path loss in sea water for $f = 1000$ Hz and coil radius $r = 1$ m, is 10 times higher with fading as compared to the path loss without fading in [8]. For both the figures the average sensing range $r_a$ is assumed to be 4.5 m.

Figure 4 depicts the variation of path loss for both sea and fresh water with increasing frequency and different values of $\sigma_i$. The plots are obtained for $N = 250$ and $\alpha = 1.5$ m. It is clear from the figure that with the increase in the frequency, the path loss increases for both sea water and freshwater environment. However, the path loss increases significantly with the increase in the value of fading parameter $\sigma_i$ irrespective of $f$. For an increment in fading parameter $\sigma_i$ from 0 dB (i.e., without fading) to 6 dB, the rate of increase in path loss in fresh water is 46.26% and in sea water it is 37.5%, respectively. The percentage increment in path for sea water in comparison to fresh water for $\sigma_i = 6$ dB is almost $\sim 19\%$. 

\[ 4.5 = 1039 \]
In sea water, the conductivity increases due to increased salinity, which results in opposed eddy current. This causes further attenuation of the communicating signal and worsens at low frequencies. In Figure 5, the effect of water conductivity on path loss due to salty sea water is illustrated. Here, the conductivity ($\sigma$) ranges from 0.1 to 4 S/m. The path loss increases with the increase in conductivity due to the opposed eddy current in sea water. It is further observed that path loss decreases with increase in frequency in sea water. The numerator and denominator inside log in Equation (17) both increases with frequency, but the numerator increases more quickly and hence increasing frequency results decrease in the path loss. Here, number of turns in the coil antennas are considered as $N = 1000$.

Figure 6 shows the variation of coverage probability with number of deployed sensor nodes for fresh water (red lines) and sea water (blue lines). The characteristics are plotted for two different frequencies $f = 1$ KHz and 500 Hz, respectively. The number of turns for both the transmitter and receiver coils are considered as $N = 1000$. It is observed that the coverage probability ($P_c$) for both fresh water and sea water increased with the increase in number of sensors and frequency. The sensing coverage in fresh water is more compared to seawater as the losses in seawater are high due to the generated eddy current by the conductive salty water. It is also observed that the increase in coverage due to the increase in frequency is not much significant as for sea water as compared to the fresh water. The results are obtained by considering the conductivity of the sea water $\sigma = 4$ S/m and the value of fading parameter $\sigma_r = 4$ dB, respectively.

Coverage as a function of fading ($\sigma_r$) is shown in Figure 7. It is observed that coverage obtained by the underwater sensor networks falls sharply at $\sigma_r = 4$ dB for both the frequencies $f = 1$ KHz and 2 KHz respectively. The coverage degrades severely with further increase in $\sigma_r$. Coverage provided by the network is almost inversely proportional to the value of $\sigma_r$. These graphs are obtained for freshwater environment. Coverage will further degrade in sea water due to the increased conductivity and opposed eddy current. It can be concluded from the figure that the impact of fading on coverage becomes more significant as the value of fading parameter $\sigma_r$ continues to increase.

4 | CONCLUSION

In this article, a fading channel model for UWSNs using MI as the communicating media is proposed. It is observed that the path loss in underwater environment depends on multiple factors such as transmitter and receiver coil distance and coil radius, number of turns in the coil antennas, the operating frequency and also on the obstacles present in the underwater environment. The achievable coverage by the sensor network decreases as path loss increases. It further decreases under the influence of fading and significantly degrades at higher frequencies. So a proper channel model considering fading is required for the performance measures of an underwater WSN. In case of sea water due to high electrical conductivity, the coverage achieved by the sensor network is less as compared to fresh water. In other words, for attaining the same coverage in sea water deployment of more sensor nodes in comparison to the fresh water is required. To maintain a reliable communication between the transmitter and receiver.
sensors in the fading environment, the increase in the number of turns of the coil antennas and coil radius can significantly make an improvement.

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