Radio Communication Model for Underwater WSN

Carlos Uribe and Walter Grote, *Member, IEEE*

***Abstract*— Underwater Wireless Sensor Networks (UWSN) experience severe communication problems due to large acoustic or electromagnetic (EM) signal attenuation. The propagation of acoustic signals in submarine media is possible with very low frequency signal carriers only, therefore reduced bandwidth, low transmission rates, thus extending transmission duration and diminishing battery life. Requirements to increase transmission data rates for UWSN have made it attractive to explore the possibilities of higher frequency EM transmissions. Recent experiments show that huge EM signal losses are to be expected in the near field of the transmitting antenna, however experiencing little additional reductions thereafter. The lack of a unified simple analytical model based on Maxwell's equations that can be used as a design tool for these wireless submarine links, validated against published experimental results, is a problem that has been solved in this paper.**

***Index Terms*— Submarine Electromagnetic Wave Propagation, Underwater Wireless Sensor Networks (UWSN)**

I. Introduction

Underwater wireless sensor networks (UWSN) have a broad range of possible applications in environmental research, coastal surveillance, real-time control of unmanned underwater vehicles (UUV), submarine and surface vessels, etc. However UWSN experience severe communication problems due to the large signal attenuation in water, regardless of whether the transmissions are of acoustic or electromagnetic nature. Transmission powers in UWSN exceed equivalent free space requirements by at least one order of magnitude. In deep waters acoustic signals only propagate well at very low frequency signal carriers, which reduce signal bandwidth and transmission rates, thus extending communication time, which shortens battery life. In shallow waters acoustic signals not only attenuate but are also subject to ambient noise. Recent requirements to increase transmission data rates for UWSN have made it attractive to explore the possibilities of higher frequency transmissions using electromagnetic (EM) instead of acoustic signals. The advantage of using higher frequencies is the fact that larger transmission bandwidths, higher transmission rates and lower energy consumptions are possible. Also, in shallow waters, EM signals do not experience as much interference as acoustic communications. However it is to be expected that submarine EM propagation will experience very high signal attenuation due to the fact that saline water is conductive.

Submarine radio communication propagation models were subject of intense research in the years 1950 to 1970. Seawater is a conductive medium with large electromagnetic signal attenuations, which increase with frequency, [15]. There have been several attempts to develop underwater EM signal propagation based communication models. Wait developed a model that establishes that the main propagation is accomplished by means of a so called Lateral EM Wave, which travels on the sea surface, making it thus possible to reach long distances, [3], [6]. However, for this to happen, the signal propagation must be in the extremely low frequency (ELF) range, which for UWSN applications has two significant drawbacks: low transmission rates and large antennas. Gabillard [7] and Siegel [9] mention that relatively lower attenuation windows are possible at a few MHz frequencies for short-range communications, based on measurement outcomes of experiments performed in the 1970's. Al-Shamma'a [10], [12] and Lucas [14] developed an experimental research programme showing that underwater links were achievable without detecting a lateral wave contribution. Measurement outcomes from this experiment show that large signal losses for distances less than 10 m away from the transmitter are experienced, but thereafter attenuations are relatively low, making it possible to cover distances up to 100 m. In spite of that, no unified analytical model describing underwater EM propagation has been developed so far, that can be validated by experimental results, to our best knowledge. The contribution of the present paper is a simple unified analytical EM propagation model for submarine applications. This model should be extremely useful for practical UWSN design since it allows predicting path losses to be calculated quite accurately for all distances that can be validated by existing experimental data. The structure of this publication is the following: in section II a brief summary of the EM underwater propagation research is presented. Section III deals with EM propagation fundamentals. In section IV an analytical underwater EM model is proposed, evaluated and validated against experimental data. The relevance of these findings is discussed in section V and final conclusions are drawn in section VI.

II. A Brief History in Submarine Radio Communication

Communication by means of electromagnetic waves between antennas submerged in a conducting medium has been a subject of research since the work of Sommerfeld in 1909, who analyzed the radiation of electric dipoles located at the boundary surface separating two media, [1]. Moore and Blair studied the problem of an ELF communication between antennas immersed in a conducting half space medium, [3]. The analysis was made under the assumption that the main

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Carlos Uribe is a Chilean Navy Officer, Master´s Degree student with the Electronic Engineering Department of Universidad Técnica Federico Santa María, Valparaíso, Chile, (e-mail: carlos.uribem@alumnos.usm.cl).

Walter Grote, is with the Electronic Engineering Department of Universidad Técnica Federico Santa María, Valparaíso, Chile, (e-mail: walter.grote@usm.cl).

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path of communication between submarine antennas is made up a lateral wave consisting of 3 components: 1) from the transmitting dipole directly to the sea surface, 2) a wave that travels along the sea surface, 3) from the sea surface to the receiving dipole in a direction normal to the water surface. According to this model, the direct path experiences a much larger attenuation than the lateral wave. No reflected wave from the sea bottom was considered since it would experience even a larger attenuation than the direct path. Due to the fact that ELF communication was considered, the displacement current that can be associated to a lossy conductive medium was neglected.

The normal concepts of antenna radiation resistance, gain, and pattern need to be restated in a conducting medium, as Moore pointed out in [4]. In a later publication, Moore makes a comprehensive survey of underwater EM communication at very low frequency (VLF), assuming 3 communication modes: 1) surface to submarine 2) submarine to surface and 3) submarine to submarine lateral wave propagation, [6]. When antennas are embedded in a lossy conductive media they need to be insulated. Wait studied a magnetic dipole antenna placed inside a spherical insulating cavity immersed in an infinite conducting medium, showing that the EM fields are independent of the characteristic of the insulation for an antenna diameter much less than the radiation wavelength in the conducting media in [2], [5]. He determined the radiated power of the insulated dipole solely due to the conduction current. Dunbar analyzed the performance of submarine magnetic loop antennas, obtaining consistent theoretical predictions of the generated EM field components as compared to experimental measurement results at VLF range in near field, in [8]. Karlsson reinforced the idea that the most radiation efficient antenna is the magnetic dipole, when immersed in conductive lossy media, [11]. Gabillard, Degauque and Wait established that the telecommunication possibilities using submarine or underground antennas depend heavily on the operating frequency in [7]. The authors distinguished two possible transmission windows at low and high frequency and therefore the assumption that the sea is a homogeneous medium with a constant conductivity is no longer valid above a certain frequency.

An interesting experimental work that shows the far-field behaviour of an EM wave propagated through seawater in the range of MHz has been published by Al-Shamma'a in [10], [12] and Lucas, [14]. The results show that a very large signal reduction is to be expected at distances less than 5 m, with relatively little additional attenuation from there on to 100 m, Fig. 1. According to the authors, no contribution could be attributed to a lateral wave, as was postulated by Moore in [3], [6]. Instead, they claim that this behaviour might be explained by seawater behaving like a lossy conductor at close range – due to the intensity of the EM field from the transmitting antenna – and as a dielectric thereafter, [10], [14]. Disagreeing with the explanation given in [10], Somaraju and Trumpf developed a model for seawater permittivity based on the Double-Debye model, in which case the path loss can only be attributed to the temperature and salinity of seawater and the frequency of the EM wave, [13]. To demonstrate this behavior, the authors developed a series of experiments to

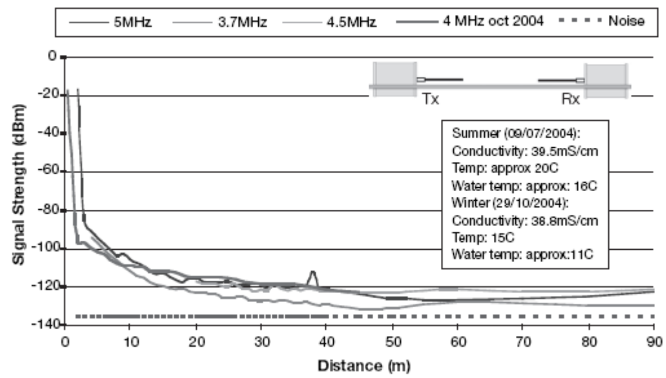

Fig. 1. Signal strength as a function of distance to transmitter antenna, [14]

verify the change in the conductivity of seawater at high frequency, but could not experimentally explain large losses as observed by Al-Shamma'a in [10].

The discussion on this topic and the lack of a submarine unified EM wave propagation model that can be useful for the design of UWSN is a good opportunity to develop one that can be validated against the existing experimental data.

III. Fundamentals of EM Wave Propagation

Maxwell's fundamental EM wave propagation equations, considering the harmonic time factor are, [15]:

$$\begin{aligned} \nabla \times E &= -j\omega\mu H & \nabla \bullet E &= \frac{\rho}{\varepsilon} \\ \nabla \times H &= (\sigma + j\omega\varepsilon)E + J & \nabla \bullet H &= 0 \end{aligned} \qquad (1)$$

where $\boldsymbol{E}$ and $\boldsymbol{H}$ are the electric and magnetic field intensity vectors respectively, σ, μ and ε are the constitutive medium parameters, and $\boldsymbol{J}$ is the impressed current density vector. Considering a Magnetic Hertz Vector $\overline{\Pi}^*$ which has only one component Π^*_z and assuming a small loop of current of area dA and circulating current I, that is equivalent to an infinitesimal electric dipole aligned to the axis z, the magnetic hertz vector is:

$$\Pi^*_{(x,y,z)} = \hat{a}_z \frac{IdA}{4\pi r} \exp(-\gamma r) \qquad (2)$$

where γ is the propagation constant, defined as:

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)} = \alpha + j\beta \qquad (3)$$

The parameters σ (conductivity); $\mu = \mu_r \cdot \mu_0$ (permeability) and $\varepsilon = \varepsilon_r \cdot \varepsilon_0$ (permittivity or dielectric constant) are normally considered fixed, but actually conductivity and permittivity are dependent on other variables, as stated in [7], [13]. If the medium is not free space the propagation constant γ is a complex quantity with α (the attenuation factor) and β (the phase factor) defined by (4), [15].

$$\alpha = \omega\sqrt{\mu\varepsilon}\left\{\frac{1}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right]\right\}^{\frac{1}{2}} \quad \left(\frac{\text{Np}}{\text{m}}\right)$$

$$\beta = \omega\sqrt{\mu\varepsilon}\left\{\frac{1}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}+1\right]\right\}^{\frac{1}{2}} \quad \left(\frac{\text{Rd}}{\text{m}}\right) \quad (4)$$

The electric and magnetic field components are given by:

$$E = -j\omega\mu\nabla\times\Pi_z^*$$
$$H = -\gamma^2\Pi_z^* + \nabla\nabla\bullet\Pi_z^* \quad (5)$$

Consider the field generated by an infinitesimal magnetic dipole immersed in a homogeneous conducting medium such as sea water. Developing (2) and (5) in spherical coordinates, the electric and magnetic field components turn out to be according to (6), [5].

$$E_\phi = -j\omega\mu\frac{IdA}{4\pi\mathrm{r}^2}(1+\gamma\mathrm{r})\exp(-\gamma\mathrm{r})\sin\theta$$
$$H_r = \frac{IdA}{4\pi\mathrm{r}^3}(1+\gamma\mathrm{r})\exp(-\gamma\mathrm{r})\cos\theta$$
$$H_\theta = \frac{IdA}{4\pi\mathrm{r}^3}\left(1+\gamma\mathrm{r}+\gamma^2\mathrm{r}^2\right)\exp(-\gamma\mathrm{r})\sin\theta$$
$$E_r = E_\theta = H_\phi = 0 \quad (6)$$

From these equations it is possible to establish a propagation model subject to the conditions experienced in the experiments described in [10], [12], [14].

IV. Submarine Propagation Model

To develop and validate the propagation model we will assume that both insulated magnetic dipoles are co-planar (θ = 90º) and parallel to the sea surface. Also, the propagation media is assumed homogeneous and isotropic. We consider the theoretical background of [5], with both the displacement and conduction current, because the large signal losses at close range from the transmitter are best explained by a lossy conducting media, while the flattening of the signal losses at larger distances fit better to dielectric phenomena.

Considering the electric field component in (6), and assuming that the received signal behaves as a uniformly distributed plane wave, the average power density received can be calculated as:

$$\left|E_\phi\right| = \frac{\mu\omega IdA}{4\pi\mathrm{r}^2}\exp(-\alpha\mathrm{r})\sqrt{(\beta\mathrm{r})^2+(1+\alpha\mathrm{r})^2}\sin\theta \quad (7)$$

$$\underline{S} = \frac{\left|E_\phi\right|^2}{2}\exp(-2\alpha\mathrm{r})\,\mathrm{Re}\left\{\frac{1}{\eta_c^*}\right\} \quad \left(\frac{\text{W}}{\text{m}^2}\right) \quad (8)$$

where η_c is the intrinsic complex impedance, [15].

$$\eta_c = \sqrt{\frac{j\omega\mu}{\sigma+j\omega\varepsilon}} \quad (9)$$

The average power received is:

$$\mathrm{P}_{Rx} = S_{av}\cdot\mathrm{A}_e \quad (\mathrm{W}) \quad (10)$$

where A_e is the Effective Area of the receiving antenna, which is defined as:

$$\mathrm{A}_e = \frac{G_{Rx}\lambda^2}{4\pi} \quad \left(\mathrm{m}^2\right) \quad (11)$$

The received average power P_{Rx} due to the direct wave emitted by a 5 W, 5 MHz transmitter is obtained by evaluating (10), by means of (7), (8),(9), (11) and then plotted for an experiment setup as described in [10], [12], [14] and standard propagation parameters, as summarized in table I.

Evaluation of P_{Rx} as compared to the 5 MHz experiment outcomes shown in Fig.1 is shown in Fig. 2. The green line represents the measurement outcomes presented in [12], [14] and the blue line represents the outcome of an evaluation of (10) obtained for a direct wave propagation model for the experiment scenario.

TABLE I
Reference Parameters for submarine EM Propagation

Symbol	Quantity	Units	Sea Water
σ	conductivity	S/m	4
μ_0	permeability	H/m	$4\pi\cdot10^{-7}$
μ_r	relative seawater permeability		1
ε_0	permittivity	F/m	$8.854\cdot10^{-12}$
ε_r	relative seawater permittivity		81

Clearly, the steep slope of (10), associated to the Maxwell equation representing an EM wave propagating in a highly conductive media almost matches the near field behaviour of the experimental results described in [10], [14]. However the signal attenuation for distances greater than 3 m is very different. Fig. 2 shows only the initial signal reduction results of the analytical model to stay within the resolution of Fig. 1, but evaluation of (7) for distances beyond 3 m just keep the same tendency as shown for the first 3 m. In fact, after 10 m the measured received power experiences signal reductions of about 25 dB while increasing the distance up to 100 m, whereas the calculated ones grow exponentially due to the strong dependency on the attenuation factor exp(-2αr) of (7).

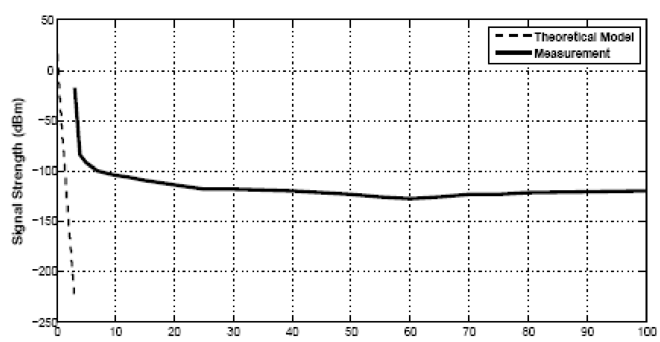

Fig. 2. Comparison of analytical results of direct wave EM signal propagation for conductive media with experimental results at 5 MHz, [12]

An EM signal propagation model that combines both effects: large attenuation at near field due to conducting media and a far field characteristic, which can be associated to transmission in a dielectric medium seems to be a good idea to develop. Lucas in [14] explains a model that represents submarine EM transmission for different carrier frequencies accurately. However, from the point of view of underwater link budget design, this analytical model is not similar to the well known path loss equation in free space that is used in (8) through (10), except for the near field attenuation factor exp(-2αr) introduced in (7).

A different approach is to associate the transition from a conducting to a dielectric media to the intensity of the electric field. However, this approach will turn the non-linear EM field equations into complicated expressions due to the feedback involved. An alternative idea is to introduce only minor changes to the EM signal propagation models presented in [7], [10], [13], to make the attenuation coefficient α distance dependent to represent the transition from near to far field, (10):

$$\alpha = \xi\left(\frac{1}{\mathrm{r}_0 + \mathrm{r}}\right) \qquad (10)$$

where r_0 and r are distances, while $\xi = \alpha \cdot \mathrm{r}_0$ is a factor, evaluated from α in (4), assuming r = 0 in (10). The value of r_0 will be picked within the transition region from near to far field. A meaningful parameter is the signal wavelength in seawater, which at 5 MHz is λ = 0.705 m. Evaluating (8) using α as defined by (10), with $\mathrm{r}_0 = \lambda$ we get Fig.3. It shows that the evaluation of (7) through (10) matches experimental results published in [10], [12], [14] quite closely. The sensitivity to the exact value of r_0 is not significant, as long as this value is picked in the neighborhood of a wavelength. Actually, it is not possible to distinguish the 0.7λ ≈ 0.5 m curve from the λ ≈ 0.705 m one. Also, if r_0 is varied tenfold in the range of 0.7λ ≈ 0.5 m to 7λ ≈ 5 m, the shape of the analytical curve remains, but with loss of accuracy as r_0 increases its value, an observation that reinforces the decision of selecting $\mathrm{r}_0 = \lambda$.

To further validate the model, short distance attenuations are measured for short submarine links, showing precisely the transition from near to far field effect at different frequencies and conductivities in [10], Fig.4. If the model developed in (7) to (10) is applied to the experiment conditions specified for

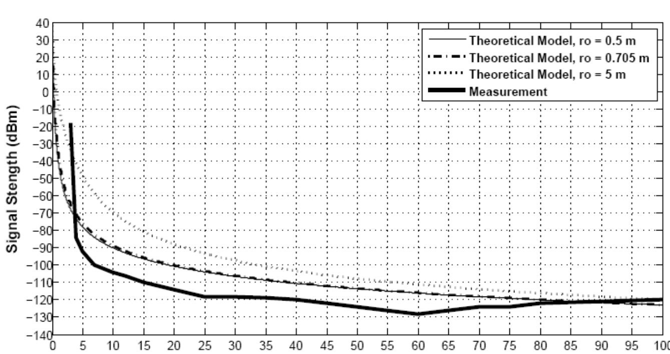

Fig. 3. Comparison of analytical results of unified EM signal propagation model with experimental results at 5 MHz, [12], [14]

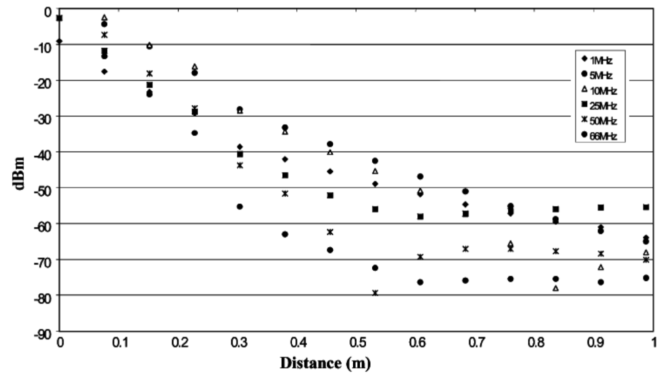

Fig. 4. Received power levels for different transmission frequencies, loop antenna (0.35 m diameter) in salt water (σ = 1 S/m), transmission power is 13 dBm, [14]

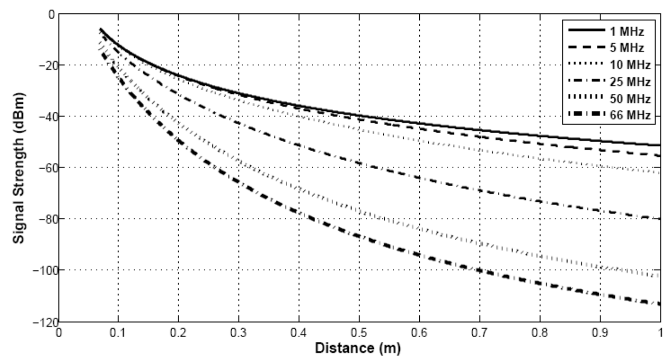

Fig. 5. Evaluation of (7) to (10) model, using identical transmission parameters as in Fig. 4, except antenna design for 25 MHz curve

Fig.4, using $\mathrm{r}_0 = \lambda$, the curves of Fig.5 are obtained.

From observation of figures 3 to 5, it can be stated that the model based on equations (7) to (10) predicts the expected path losses quite accurately, except for the 25 MHz curve of Fig.5, for which case it is reported in [10] that the antenna was specially adapted to operate at 25 MHz, an effect that is not considered in the set of equations (7) to (10).

It can be therefore concluded that the model based on equations (7) to (10) is quite precise, at least against the data it has been validated, which considers frequency, conductivity and distance parameter changes. It also is a relatively simple extension of the existing free space model. This makes it a valuable tool for design of UWSN. The remaining question to answer is, how useful is EM propagation for UWSN as compared to acoustic transmission?

V. UWSN Communications: Acoustic or EM?

Table II summarizes relative merits of both methods of submarine communications, based on either acoustic or EM wave propagation, [17].

One of the advantages of using submarine EM rather than acoustic wave communications is related to the use of higher carrier frequencies, which in turn allows for larger bandwidths and, as a consequence faster transmission rates.

TABLE II
THEORETICAL COMPARISON OF ACOUSTIC AND EM WAVES IN SEAWATER ENVIRONMENTS

	Acoustic	Electromagnetic
Nominal Speed (m/s)	~ 1.500	~ 33.333.333
Power Loss	> 0.1 dB/m/Hz	~ 28 dB/1km/100MHz
Bandwidth	~ kHz	~ MHz
Frequency Band	~ kHz	~ MHz
Antenna Size	~ 0.1 m	~ 0.5 m
Antenna Complexity	Medium	High
Effective Range	~ km	~ 100 m
Data Rate	Up to 100 Kbps	Up to 10 Mbps
Major Hurdles	Bandwidth-Limited Interference-Limited	Power-Limited

TABLE III
PREDICTED DATA RATE AND RANGES [16]
RADIO MODEM S1510 – S5510

Range	<1 m	10 m	50 m	200 m	2 Km	10 Km
RF Tx rate in Seawater) kbps	Up to 10^5	10^2	1-5	10^{-1}	10^{-2}	10^{-3}
Applications	- AUV - Wireless connector	- AUV data download -UWSN	- Divers Comm.	- AUV control - Telemetry Navigation Beacons	- Seabed Telemetry	- Seabed Telemetry

Additionally, underwater EM wave propagation speeds exceed by 4 orders of magnitude the speed of acoustic waves reducing delays significantly. Another convenient feature of EM propagation is that in shallow waters it is more immune to interference signals. The fact that the EM coverage is less than the one of acoustic transmissions can be considered a disadvantage or a convenient feature. The disadvantage can be worded like this: it is not a good idea to try to cover large distances with EM transmissions, because it does not show a good tradeoff between distances to be covered and transmission rate, as Table III shows for modems that are available in the market, [16]. However, if a dense UWSN is going to be deployed, it is convenient, because it allows for frequency reuse in a reduced space.

One last important factor to consider is the impact on lower energy consumption of UWSN devices using RF communications because it extends battery lifespan. Considering that both radio and acoustic modem may operate in the same power range, transmission times are less whenever a higher transmission rate can be used. Therefore it seems that acoustic transmissions may be used in the future for underwater links covering distances that exceed 200 m, while RF communication may be used for distances less than 200 m.

VI. CONCLUSION

In this paper we developed a new unified EM wave propagation model for submarine radio communications that describes the path losses between transmitter and receiver antenna quite accurately both in the near and the far field, as compared to experimental data available. The model is robust to frequency, conductivity and distance parameter changes. To our best knowledge we have not been able to find such a comprehensive undersea EM signal propagation model in the existing literature, thus making it a valuable tool for UWSN designers to dimension telecommunication needs and requirements of submarine links.

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