DRDC-RDDC-2015-P002

Simulation of Communications Using Underwater Acoustic Signals Impaired by Wide Band Attenuation

Jie Huang, Michel Barbeau, Stéphane Blouin, Craig Hamm and Martin Taillefer

***Abstract*— We study simulation of underwater communications using acoustic signals impaired by attenuation and multipath propagation. Attenuation is sensitive to the source-receiver separation distance, sound speed profile and signal frequency. Multipath propagation is affected by reflection and refraction due to the environment boundaries, sea surface and seabed, and sound speed profile. Simulation of attenuation together with multipath propagation is approached by translating acoustic signals from the time domain to the frequency domain, applying attenuation on frequency components and translating attenuated frequency components back into the time domain. This algorithm is repeated for each copy of a signal created due to multipath propagation. Using this approach, we have developed a simulation of underwater acoustic data signals. The implementation has been done using the MATLAB and the BELLHOP software. Simulation results have been obtained and are compared with a universal model of signal quality.**

***Index Terms*— Underwater sensor network, underwater communications, acoustic waves, simulation.**

I. INTRODUCTION

Underwater Sensor Networks (USNs) are a promising technology for numerous applications including monitoring of the undersea environment for pollution reduction and control [9]. USNs use acoustic signals for communications. We study the simulation of underwater communications using acoustic data signals impaired by frequency dependent attenuation and multipath propagation. Attenuation is sensitive to propagation distances, sound speed profiles and transmission frequencies. It is not flat across a signal bandwidth. Multipath propagation of underwater acoustic waves – the phenomenon in underwater acoustic communications whereby signals are received by more than one path – is one of the greatest sources of communication errors. Multipath propagation is influenced by reflection, at sea surface and seabed, and refraction due to conditions such as water temperature, salinity, current, depth, surface waves, partial ice cover and seabed material.

The specific problem addressed in this paper is the evaluation, through simulation, of communications using underwater acoustic data signals impaired by wide band signal attenuation and multipath propagation. The signals are said *wide band* because their bandwidth is relatively large compared to their center frequency [12].

Simulation of frequency dependent attenuation together with multipath propagation are approached by i) translating the acoustic signals from the time domain to the frequency domain, using a Fast Fourier Transform (FFT), ii) applying attenuation on frequency components of the acoustic signal and iii) translating the frequency components back into the time domain. This procedure is repeated for each copy of a signal generated due to multipath propagation. The approach is *brute force*, because of the FFT computational cost which is $\mathcal{O}(n \log n)$, where n is the number of FFT points.

Following this approach, we have developed a simulator of underwater acoustic data signals. The implementation has been done using the MATLAB software and BELLHOP ray tracing program. MATLAB and BELLHOP complement each other. MATLAB facilitates the implementation of the signal processing related features of the simulation, such as modulation and demodulation [5]. BELLHOP is a software tool that addresses underwater multipath propagation of acoustic signals, taking into account environmental parameters such as bathymetry, sound speed profile, seabed type and sea surface type [8]. The communication model is based on work in a companion paper [2]. It includes three parts: a Phase-Shift Keying (PSK) modulator, a channel simulator and a PSK demodulator. The modulator and demodulator are original work of Borrowski [3]. This paper's contribution is in the channel simulator. We simulate attenuation taking into account the source-receiver separation distance, sound speed profile and signal frequency. We simulate multipath propagation affected by reflection and refraction due to the environment boundaries, sea surface and seabed, and sound speed profile. For this part of the work, we use a BELLHOP-MATLAB wrapper developed by Maritime Way Scientific.

Related work is reviewed in Section II. The problem is detailed in Section III. Our simulation method is discussed in Section IV. Preliminary simulation results are reviewed in Section V. We conclude with Section VI.

II. BACKGROUND AND RELATED WORK

Multipath propagation is the phenomenon in underwater acoustic communications whereby signals are received by several paths. Multipath propagation is caused by reflection and refraction. They are determined by the environment boundaries, sea surface, seabed, and sound speed profile. The sound speed profile determines the acoustic wave propagation speed as a function of depth. The sound speed

Jie Huang and Michel Barbeau are with School of Computer Science, Carleton University, K1S 5B6, Ottawa, Ontario, Canada `jiehuang4@cmail.carleton.ca`, `barbeau@scs.carleton.ca`

Stéphane Blouin is with DRDC Atlantic Research Centre, Dartmouth, NS, Canada B2Y 3Z7 `stephane.blouin@drdc-rddc.gc.ca`

Craig Hamm and Martin Taillefer are with Maritime Way Scientific Ltd., 1420 Youville Drive (Unit 5), Ottawa, Ontario, Canada K1C 2X8 {`craig.hamm`, `mtaillefer`}`@maritimeway.ca`

978-1-4799-5829-0/15/$31.00 ©2015 IEEE

depends on water temperature, salinity and current. Models of reflection and refraction are discussed hereafter.

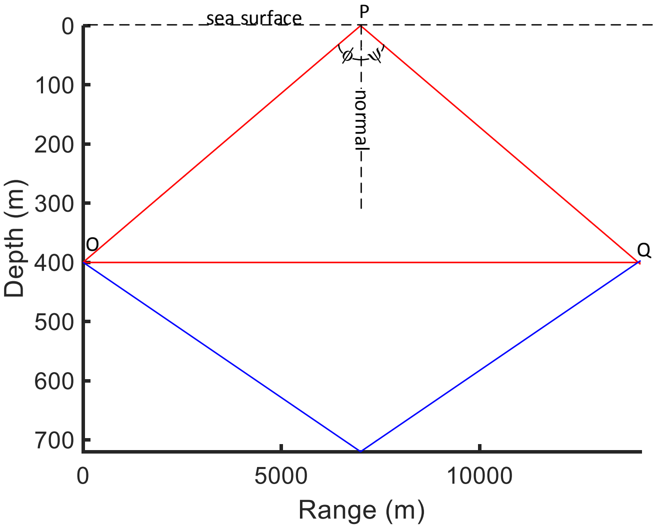

Fig. 1. Sea surface and seabed reflection.

Reflection causes changes in the direction of a wave propagation path. Every direction change occurs at the interface between two media of different types. For underwater communications, there are two interfaces, the sea surface and seabed. Figure 1 pictures a reflection case. The x-axis represents distance (meter). The y-axis represents water depth (meter). This example illustrates the effect of reflection alone. It is assumed that sound speed is invariant. Hence, there is no refraction. Sea depth is 720 meters. There is a signal source at a depth of 400 meters, left (point O). There is a signal receiver also at a depth of 400 meters, but located 14 kilometers at the right of the source. The figure shows three wave-paths connecting the source and receiver (points O and Q) represented by three rays: a direct path (horizontal line), a sea surface-reflected path (inverted V) and a seabed-reflected path (V shaped). The *incident ray* OP is reflected by the sea surface at point P. The resulting *reflected ray* is PQ. The *normal* is an imaginary line originating a point O and perpendicular to the sea surface. Together with the incident ray, they define the incident angle ϕ. Together with the reflected ray, they determine the reflection angle ψ. These two angles are equal.

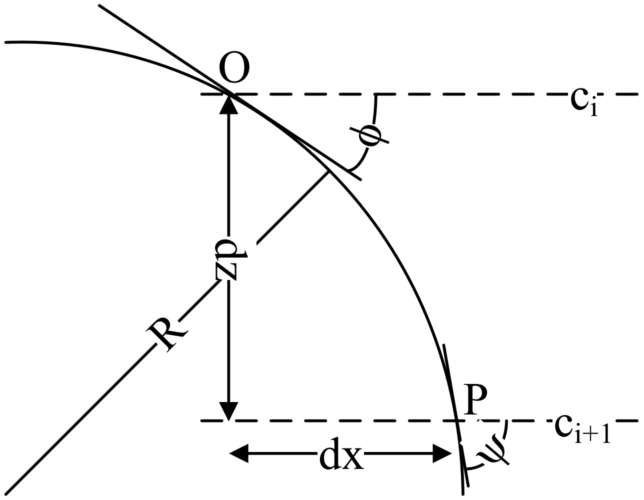

Fig. 2. Underwater refraction.

Like reflection, refraction causes changes in the direction of a wave propagation path. In contrast, the direction changes occur in the transmission medium, i.e., in water, between the sea surface and seabed. The changes are determined by the sound speed gradient, which is rate of sound speed change with the water depth. Note that sound speed is assumed to be constant with horizontal distance. Underwater refraction curves sound rays. Refraction is governed by Snell's law [13]. Figure 2 pictures a refraction model. Two discrete water levels are pictured. The top horizontal line represents a level where sound speed is c_i meters per second. The next lower level has sound speed c_{i+1} meters per second. These two lines define a vertical interval which length is dz meters. The *sound speed gradient* is

$$g = \frac{c_{i+1} - c_i}{dz} \text{ s}^{-1}.$$

It is a change of sound speed, $c_{i+1} - c_i$, as function of vertical distance, dz. Units are inverse seconds (s^{-1}). The angle of the ray, when it crosses the top horizontal line (point O), is ϕ degrees, with respect to the line. The radius of the arc OP is

$$R = \frac{-1}{g} \cdot \frac{c_i}{\cos\phi} \text{ meters.}$$

Note that the radius is inversely proportional to the sound speed gradient, that is to say, a larger sound speed gradient causes a curvier change of direction. The angle of the ray when leaving the interval, at point P, is

$$\psi = \arccos\left(\cos\phi - \frac{dz}{R}\right) \text{ degrees.}$$

The horizontal distance traversed by the ray corresponds to

$$dx = R\,(\sin\psi - \sin\phi) \text{ meters.}$$

Example: Let dz be one meter, c_i be 1500 m/s, c_{i+1} be 1495 m/s and ϕ be 45 degrees. The sound speed gradient is -5 s^{-1}, radius R is 424 meters, leaving angle is 45.2 degress and dx is 0.9967 meter.

An example sound profile is shown in Figure 3. The sound propagation speed is shown as a function of water depth. In this example, the depth goes from zero to 720 meters. The sound speed profile is a continuous phenomenon. For computation purposes, it is interpolated by specified distinct points. Within that depth range, the sound speed varies between 1512 m/s to 1462 m/s. Given a sound speed profile, a depth and a departure angle, the propagation of a ray can be traced, interval by interval, for an arbitrary propagation distance or delay. Figure 4 shows the effect of the sound profile of Figure 3 to the propagation paths of rays. The rays are curved. Bending is stronger at low depth, because

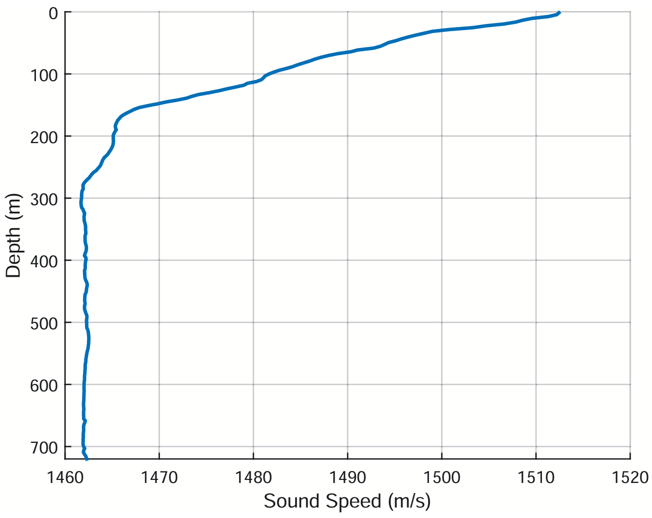

Fig. 3. Example sound speed profile.

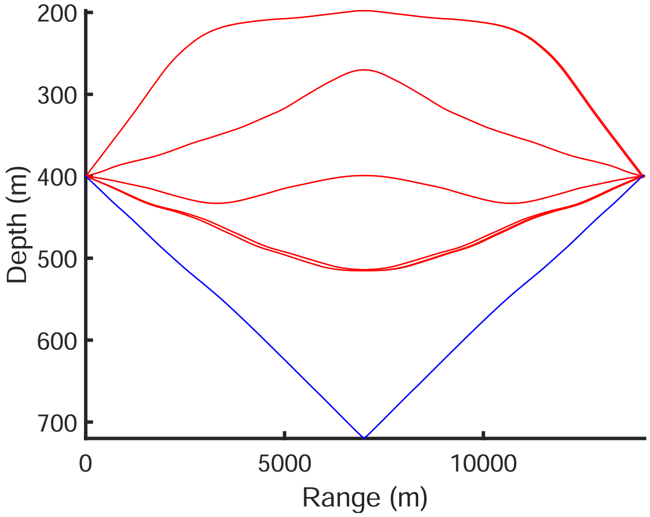

Fig. 4. Refracted rays.

of larger sound speed gradients. From 300 meter-deep, there are only slight variations of the sound speed gradient.

Our work builds upon the BELLHOP software [8], [7], which given an underwater source, traces all acoustic rays that it radiates. BELLHOP uses a *sound speed profile*. Among all the result types produced by the BELLHOP software, two of them are relevant to our work: eigenrays and attenuation. An *eigenray* is modeling an acoustic ray path from a source to a receiver.

Example eigenrays produced by the BELLHOP software are shown in Figure 5. The source-to-receiver range is 20 kilometers, the sound propagates from left to right. The depth of the source is 1200 m. The eigenrays are calculated for a range of receiver depths (zero to 5000 m in this example). The eigenrays of Figure 5 were generated using the sound speed profile of Figure 6.

For the three eigenrays of Figure 5, Figure 7 shows the travel time (second) and attenuation (dB) as a function of the eigenray. From left to right, the first stem corresponds to the eigenray with a trajectory solely subject to refraction (middle curve in Figure 5). The next two stems correspond to the sea surface and seabed reflected eigenrays. The attenuation values are the same because a hard seabed has been specified for this example.

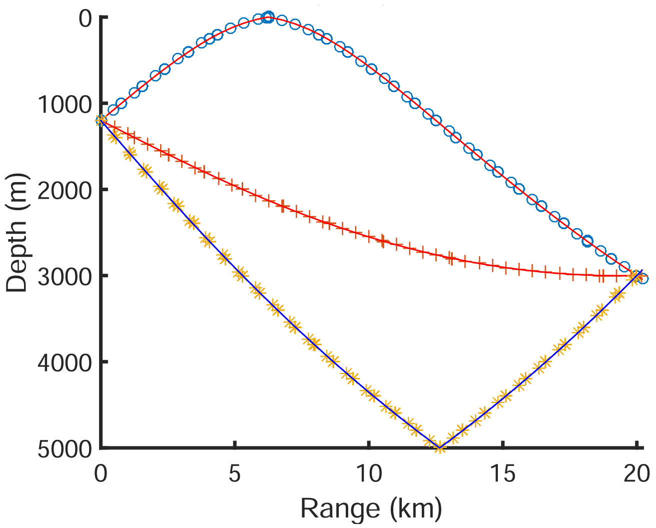

Fig. 5. Eigenrays between an underwater acoustic source-receiver separation distance of 20 kilometers. The source is 1200 m deep. The receiver depth is between zero to 5000 m.

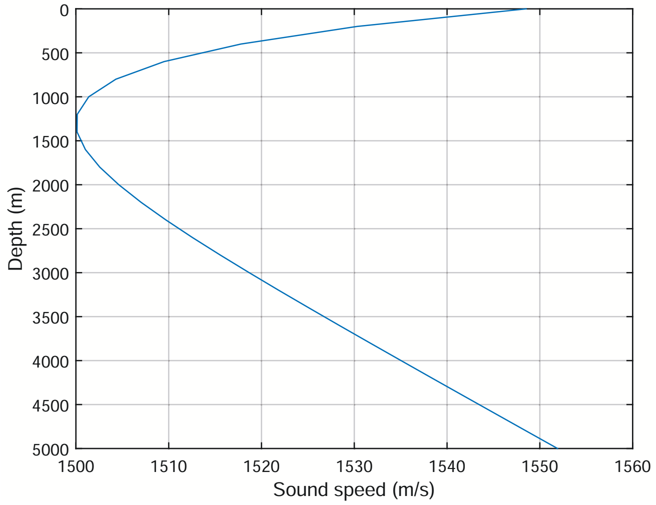

Fig. 6. An example underwater sound speed profile.

III. PROBLEM

Figure 8 shows the spectrum of an unerwater acoustic PSK signal of one kilobaud relative to a generic Very Low Frequency (VLF) center frequency `f`. The Root Mean Square (RMS) power of the signal is 1 dB re μPa.[1] Most of the energy is concentrated between plus-minus one kilohertz the

---

[1] The term *re μPa* stands for *relative to a reference pressure 1 micropascal*. The *pascal* is a unit of force per unit area, i.e., pressure. It is equal to one newton per square meter.

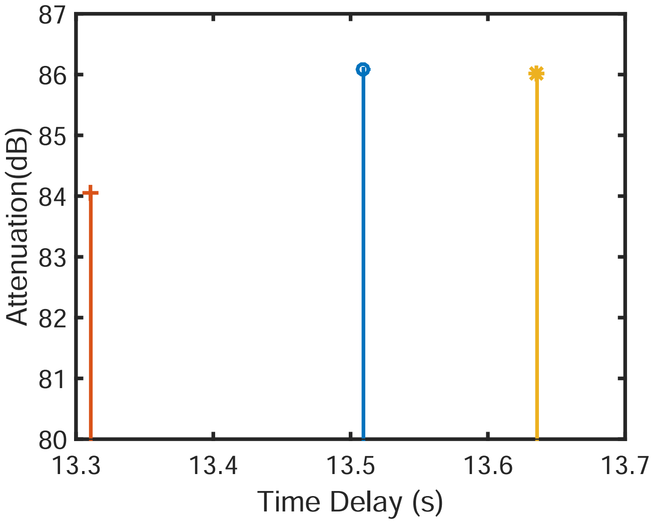

Fig. 7. Travel time (second) and attenuation (dB) as a function of the eigenray.

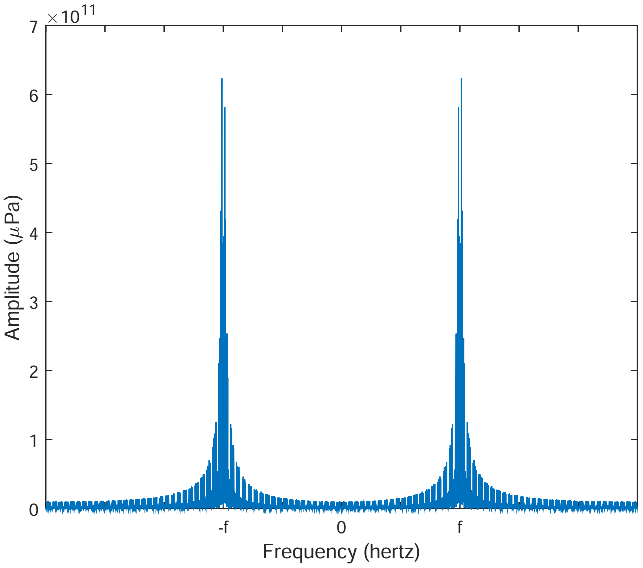

Fig. 8. Signal spectrum relative to a generic Very Low Frequency (VLF) center frequency `f`.

center frequency. On the other hand, Figure 9 shows the attenuation, relative to the generic VLF center frequency `f` (plus-minus one kilohertz), according to the BELLHOP software [8]. The diagram shows substantial variation of attenuation as a function of distance. Furthermore, there is also substantial attenuation across the bandwidth of the PSK signal. For example, at 5 kilometers, the attenuation goes from 46.7 dB to 48.5 dB. Past simulators of underwater acoustic communications, e.g., [4], calculate attenuation at the center frequency of a signal and apply the same attenuation across the signal bandwidth, e.g., between plus-minus one kilohertz the center frequency. Our goal is to simulate attenuation as a function of frequency, within a signal bandwidth, and distance.

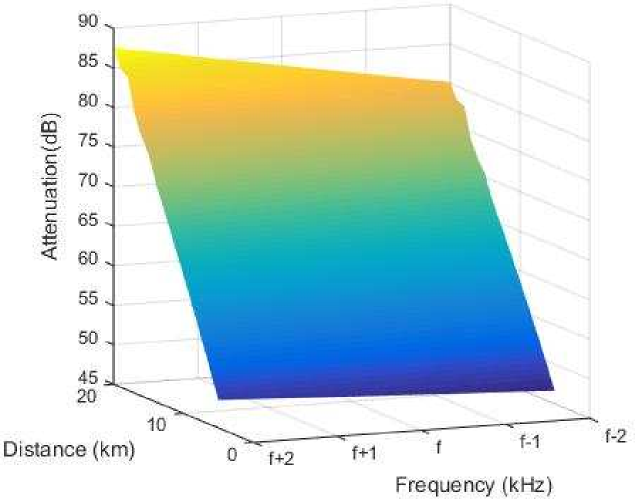

Fig. 9. Attenuation relative to a generic VLF center frequency `f` and distance (5 to 20 kilometers).

IV. METHOD

Our simulation of the underwater acoustic transmission process is implemented using the MATLAB and BELLHOP software. The simulation model is based on work in a companion paper [2]. It includes three parts: a PSK modulator, a channel simulator and a PSK demodulator. We use the modulator and demodulator as explained in [2]. Our contribution is in the channel simulation model. We are aiming to mimic the effect of underwater attenuation and multipath propagation on a wide-band signal. We translate the signal from the time domain to the frequency domain. We obtain the amplitudes of the frequencies that compose the signal. We calculate the attenuation and eigenrays for each frequency that composes the wide-band signal. For this part of the work, we build upon a BELLHOP-MATLAB wrapper developed by Maritime Way Scientific. The underwater environment is described as parameters such as the seabed type, sea surface waves, sea surface ice, bathymetry, sound profile, depth of the source and receiver, signal frequency and source-receiver separation distance. The BELLHOP software is encapsulated in the MATLAB interface functions `bellhopRay` and `bellhopAttenuation`. The signal frequency and separation distance are the arguments of the interface functions. The other environment parameters are defined in a file as a list of constants. They are loaded at run time. For example, we set the seabed as muddy sand and no sea surface waves nor ice. The sound speed profile, as the one shown in Figure 6, is specified in a file listing the sound speeds for a number of water depths.

The function `bellhopRay` is invoked to determine the eigenrays from the source to the receiver. The signal frequency and separation distance are the arguments of `bellhopRay`. The resulting eigenrays are produced in an output file. Figure 5 has been obtained by plotting the content of such a file. The eigenrays are frequency independent, but frequency can affect the step size of eigenray calculation. The BELLHOP software assumes that higher accuracy ray tracing is required for higher frequencies. That means that more accurate traces are obtained with higher frequency [6]. Invocations of the `bellhopRay` interface function provides the number of eigenrays, their coordinates, collisions with sea surface or seabed and propagation steps. Attenuation and delays are the outputs of `bellhopAttenuation` function. We also take into account noise. Hereafter, we discuss the details of attenuation data usage and noise generation in the channel simulator.

A. *Attenuation*

To analyze its effect on a wide-band signal, we determine attenuation for the various frequencies within the signal bandwidth. Therefore, after a Fast Fourier Transform (FFT), we invoke the `bellhopAttenuation` function for each FFT frequency bin. For instance, for a signal such as the one pictured in Figure 8, we call `bellhopAttenuation` for FFT frequency bins between plus-minus one kilohertz a VLF center frequency. For each frequency bin and distance, `bellhopAttenuation` outputs delays (second) and attenuation (linear form) for all eigenrays. When there are multiple paths, only the path with the smallest attenuation is picked. The corresponding attenuation factors are applied, as a function of frequency. The following MATLAB script gets the attenuation for a frequency `f` (kilohertz) and a source-receiver separation distance `d` (kilometer):

```
array = bellhopAttenuation(f,d);
% Sort delays from minimum to maximum
[delay,t_idx]=sort(array.delay);
% Get attenuation with minimum delay
attenuation = array.attenuation(t_idx(1));
```

The BELLHOP software returns amplitude values, relative to unit amplitude at the source. Attenuation values correspond to the inverses of these amplitudes. This script is executed repeatedly for each FFT frequency bin.

B. *Noise Generation*

According to the method described in [2], we generate colored noise. Gaussian white noise is generated across the band, with mean equals to zero and variance equals to two. The noise is fed through a low-pass filter to capture sensitivity to frequency, i.e., the noise becomes colored. The colored noise is added to the signal, in the time domain representation.

The noise level at the center frequency is used to calculate the E_b/N_0 ratio. The term E_b/N_0 stands for energy per bit to the noise power spectral density ratio [10]. The energy per bit (E_b) is defined as the signal power over the product of the baud rate and number of bits per symbol. That is to say

$$\frac{E_b}{N_0} = \frac{PB}{NR}.$$

Symbol P denotes the signal power (*re* μPa). Symbol N corresponds to the noise power (*re* μPa). Symbol B stands for the signal bandwidth (hertz). Symbol R represents the bit rate (bits per second).

V. SIMULATION RESULTS

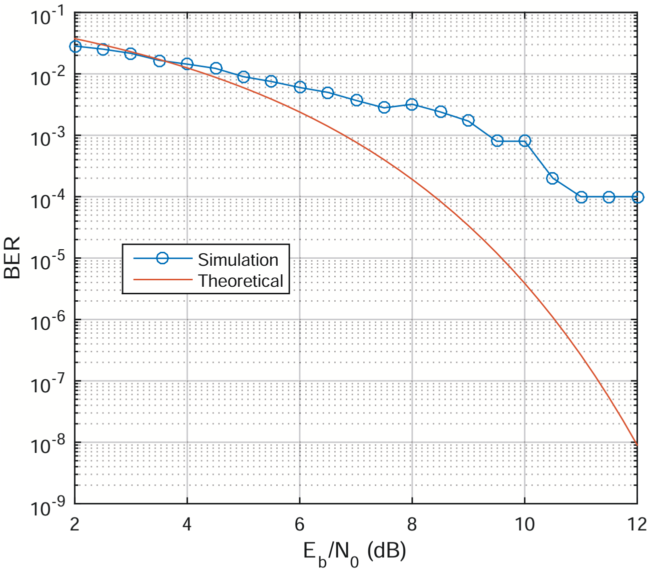

Fig. 10. BER as a function of the E_b/N_0 ratio.

The Bit Error Rate (BER) versus the E_b/N_0 ratio is a universal model of signal quality. Figure 10 plots the BER as a function of the E_b/N_0 ratio. It shows both the theoretical BER and the BER obtained through simulation. The theoretical BER is according to standard error probability function [11]:

$$P_e = \frac{1}{2}\text{erfc}(\sqrt{\gamma})$$

where P_e stands for the probability of error, γ corresponds to the E_b/N_0 ratio and *erfc* is the complementary error function [1]. The BER obtained through simulation has been obtained by randomizing the distance in the range 5 and 20 kilometer and for a generic VLF frequency. The BER was calculated repeatedly sending 10008-bit packets. The BER obtained through simulation is slightly higher than with the theoretical BER. Note that the theoretical model has been developed in a wireless context. It is used for comparison purposes with reservations, because the physical properties are different. An underwater acoustic signal is subject to colored noise. An wireless electromagnetic signal is subject to white noise. Similar results were obtained in the 8 kilometer and 10 kilometer cases.

VI. CONCLUSIONS

The objective of the work described in this paper is to simulate the propagation of underwater acoustic data signals taking into account attenuation and multipath propagation. We model attenuation as a phenomenon that is determined by distance and frequency, within a signal bandwidth. We have developed a simulation model using the MATLAB and BELLHOP software tools. The signal processing aspects, that is, modulation, channel and demodulation are implemented as MATLAB functions. A MATLAB wrapper provides functions necessary to calculate paths and attenuation associated with the propagation of an acoustic data signal in an underwater environment. The signal is converted from the time domain to the frequency domain. This transformation yields the frequency components of the data signal. Attenuation is calculated and applied to each of them individually. The signal is converted back from the frequency domain to the time domain. Colored noise is added. The attenuated signal combined with the colored noise is the output of the channel model. The work has been tested using an underwater PSK data signal.

Future works include taking into account all signal paths produced by the function `bellhopAttenuation`. The current version takes into account only the shortest delay-path. More simulations, under various scenarios, are required to refine the preliminary BER analysis.

VII. ACKNOWLEDGMENTS

We would like to thank Brian S. Borowski for sharing his MATLAB code with us. We acknowledge financial support from Natural Sciences and Engineering Research Council (NSERC) of Canada (Engage Grant).

REFERENCES

[1] M. Abramowitz and I. Stegun. *Handbook of Mathematical Functions: with Formulas, Graphs, and Mathematical Tables*. Dover Books on Mathematics. Dover Publications, 2012.

[2] M. Barbeau, S. Blouin, G. Cervera, J. Garcia-Alfaro, B. Hasannezhad, and E. Kranakis. Simulation of underwater communications with colored noise approximation and mobility. In *28th annual IEEE Canadian Conference on Electrical and Computer Engineering (CCECE)*, May 2015.

[3] B. S. Borowski. *Application of Channel Estimation to Underwater Acoustic Communicaton*. PhD thesis, Stevens Institute of Technology, Castle Point on Hudson, Hoboken NJ, 2010.

[4] B. S. Borowski. *Application of Channel Estimation to Underwater, Acoustic Communication*. PhD thesis, Stevens Institute of Technology, Hoboken, NJ, USA, 2011.

[5] MathWorks. MATLAB - The language of technical computing, 2015.

[6] M. B. Porter. The BELLHOP manual and user's guide: Preliminary draft, January 2011.

[7] M. Porter and H. Bucker. Gaussian beam tracing for computing ocean acoustic fields. *The Journal of the Acoustical Society of America*, 82(4):1349–1359, 1987.

[8] O. C. Rodriguez. General description of the BELLHOP ray tracing program, June 2008.

[9] E. Sevaldsen. Acoustics in underwater environmental monitoring. In *Proceedings of Oceans Engineering for Today's Technology and Tomorrow's Preservation (OCEANS)*, volume 1, pages I/464–I/468, Sep 1994.

[10] W. Stallings. *Data and Computer Communications*. Pearson Prentice Hall, Upper Saddle River, NL 07458, ninth edition, 2011.

[11] H. Stern, S. Mahmoud, and L. Stern. *Communication Systems: Analysis and Design*. Pearson Prentice Hall, 2004.

[12] M. Stojanovic and J. Preisig. Underwater acoustic communication channels: Propagation models and statistical characterization. *IEEE Communications Magazine*, 47(1):84–89, 2009.

[13] R. Urick. *Principles Of Underwater Sound*. McGraw-Hill Ryerson, Limited, 1983.