AquaTools: An Underwater Acoustic Networking Simulation Toolkit

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***Abstract*—High cost of development and deployment coupled with the complexity of the underwater acoustic channel makes it important to develop simulation tools which can assist in investigating underwater sensor networks and mobile autonomous underwater vehicular communications. Some recent developments have led to simulators which provide the ability to simulate mobile and stationary underwater acoustic communication, however, they do not take into account factors such as ocean acidity, salinity and temperature, which too have effects on the channel. In this paper we present an overview on the AquaTools simulation toolkit, some background on channel models utilized and an excerpt of the results obtained during testing and validation of the simulator.**

I. INTRODUCTION

The radio or optical channels are not efficient underwater since radio waves require very low transmission frequencies (30-300 Hz), very long antennae and high transmission power, while optical communication is usable only for short range communications due to the high signal attenuation. Consequently, the acoustic channel has become a common choice for wireless underwater communication.

However, volatility of channel conditions leads to high and varying ambient noise and high localized fluctuations in propagation delay due to the dependence of sound velocity on ambient temperature, salinity and acidity. Surface-bottom multi-path echoes, low-transmission speeds, narrow bandwidth and high bit-error-rates create challenges for dependable communication in the underwater acoustic channel [1]. This makes exhaustive testing of any underwater network necessary to ensure reliable communications.

Fabrication and off-shore deployment costs associated with underwater networks can be quite high. The costs of a dependable underwater acoustic modem are in the order of several thousand dollars, and off-shore deployment and recovery from a small boat can be in thousands per day. Such high costs associated with off-shore testing can be a bane to development in case revisions are necessary [2]. These costs coupled with complexity of the channel highlight the need for a simulator to accurately model the rapidly changing underwater acoustic channel. This would assist in development of systems and reduce off-shore deployment times.

Furthermore, in recent times Autonomous Underwater Vehicles (AUVs) have gained acceptance for deployments in off-shore research and exploration tasks. However, as in the terrestrial and aerial robotics fields, the maximum potential for underwater unmanned vehicles lies in cooperative multi-AUV tasks. There are also some emerging scenarios involving the use of AUVs as data mules in an underwater sensor network. The addition of mobile communication networks increases the complexities of underwater networks. Any simulator must, as such, have the ability to simulate not just static, but also mobile nodes.

Even though tools like MATLAB are very useful in understanding channel characteristics, they fall short of being able to simulate networking performance as a result of the chosen MAC layer, routing protocol and other similar parameters; they cannot even provide network traces without much effort. As such, it is necessary to develop simulators which can evaluate underwater acoustic communications from a networking perspective as well.

The recent simulators capable of performing network simulations [3], [4] do not take into account ambient temperature, node depth, ocean acidity and salinity while characterizing the channel, however, these parameters are known to have an effect on channel performance [5], [6]. Restrictions on the choice of MAC layer or absence of routing layers also point toward needed improvements. As such, the AquaTools simulation toolkit was developed to overcome these shortcomings. The AquaTools toolkit is based on ns2, a popular networking simulator and can as such make use of any MAC layer, routing layer, energy conservation schemes and other developments for the ns2 simulator as well. The AquaTools toolkit simulations can be setup via scripts and any acoustic modem's characteristics can be simulated by providing the appropriate parameters. Different mobility models can also be incorporated into the simulation.

This paper provides an overview of the different propagation and channel models utilized by the AquaTools simulation toolkit. Details on the design and usage of the AquaTools simulation toolkit will also be discussed along with some results obtained during validation and testing of the simulator.

II. RELATED WORK

Simulation and laboratory testing of underwater acoustic networks is a relatively new area, however, there already exists some effort in this area. The authors of [4] present an implementation of an interface and channel model for

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underwater acoustic networks in their $nsmiracle$ simulator. As part of their work the authors construct a channel model based upon the Thorp equation [7] and accounting for ambient noise. This $nsmiracle$ based simulator currently provides support only for MAC and PHY layer implementations and is provided along with an implementation of FDMA and ALOHA protocols. There is no support for routing and transport layer protocols available and a protocol stack needs to be implemented as well. As such, it is not possible to perform full-scale underwater network tests in this simulator.

An underwater acoustic local area network is designed and tested using OPNET's Radio Modeler in [8]. The authors of this paper design a network that consists of master and sensor nodes which utilize battery powered modems and rely upon the model of the Datasonics ATM-875 modems within the simulation. The authors assumed static network nodes and a slowly varying channel, which stays constant during a packet interval. The author's model the sound velocity as a constant, whereas, in the aquatic environment this is known to vary as per ambient conditions. Both, $nsmiracle$ and the OPNET based simulator do not provide support for modelling effects of ambient oceanic conditions and node depth, which effect the channel performance as well. Furthermore, possible node mobility is also not accounted for.

MATLAB based simulations of the underwater acoustic channel are quite popular in literature, however, mostly these are highly application specific and deal with simulating the lower layers only [9]. Even though this simulation environment provides quite an in-depth simulation of the physical and link layers, it does not provide a method for defining custom topologies, power models or methods for monitoring other factors like packet transmissions, losses and collisions that might interest the networking community and might even impact the performance of a network in the underwater channel. Additionally, no support for routing protocols is made available within MATLAB.

The shortcomings of recent simulation environments highlight the need for a flexible simulation environment that is capable of not only simulating all aspects of the network and effects of the ambient environment, but also support mobile nodes. The AquaTools simulation toolkit was developed with this goal.

III. THE CHANNEL MODEL

An accurate understanding and modelling of the underwater acoustic channel is the basis upon which all work for underwater networks is based. There exist several models for calculating and predicting the attenuation, which effects all other aspects of the underwater acoustic channel model. Furthermore, parameters from frequency, distance, depth, acidity to salinity and temperature of the underwater environment effect how the channel acts and in turn also result in changing network performance. As such, as a basis for further work, it is necessary to create suitable channel models for predicting the performance of an underwater channel. This section formulates underwater channel models and numerically compares them.

Table I
VALUES FOR REPRESENTING TYPES OF GEOMETRICAL SPREADING VIA THE GEOMETRICAL SPREADING COEFFICIENT k

	Spherical	Cylindrical	Practical
k	2	1	1.5

A. Propagation Delay

For most purposes the speed of sound in water is taken to be approximately 1500 m/s. While this is accurate within a certain range, the underwater channel is an extremely complex environment that is effected by many varying factors, primarily temperature, salinity and depth [10] and furthermore each of these factors may also be interdependent or varying across the ocean. It is, as such, important to have an accurate model of the effects of these parameters on the speed of sound in water.

The MacKenzie equation shown below provides an estimate of the speed of sound in water with an error in the range of approximately 0.070 m/s

$$\begin{aligned} v \;=\;& 1448.96 + 4.591T - 5.304 \cdot 10^{-2}T^2 \\ & +2.374 \cdot 10^{-4}T^3 + 1.340(S-35) \\ & +1.630 \cdot 10^{-2}D + 1.675 \cdot 10^{-7} \cdot D^2 \\ & -1.025 \times 10^{-2} \cdot T \cdot (S-35) \\ & -7.139 \cdot 10^{-13} \cdot T \cdot D^3 \qquad (1) \end{aligned}$$

Here, T is the temperature in °C, S is the salinity in parts per trillion, D is the depth in meters and v is the sound velocity in m/s. This model provides a good representation of the sound velocity profile in the aquatic medium and as such, was chosen as the basis of all propagation delay modelling.

B. Propagation Loss

The transmitted acoustic signal between sensor nodes in a network reduces in overall signal strength over a distance due to many factors like absorption caused by magnesium sulphate and boric acid, particle motion and geometrical spreading. Propagation loss is composed majorly of three aspects, namely, geometrical spreading, attenuation and the anomaly of propagation. The latter is nearly impossible to model and as such the attenuation, in dB, that occurs over a transmission range l for a signal frequency f can be obtained from:

$$10 \log A(l,f) = k \cdot 10 \log l + l \cdot 10 \log \alpha \qquad (2)$$

where α is the absorption coefficient in dB/km, which can be obtained from models specifically characterizing it, and k represents the geometrical spreading factor. In order to represent accurately the type of spreading that occurs, this geometrical spreading factor can be substituted with values shown in Table I. The overall propagation loss can be easily obtained when Equation 2 is used along with an appropriate attenuation model that provides the absorption coefficient α.

C. Absorption Coefficient

Attenuation by absorption occurs due to the conversion of acoustic energy within sea-water into heat. This process

Table II
FISHER & SIMMONS MODEL'S COEFFICIENTS

$$\begin{aligned}
A_1 &= 1.03 \times 10^{-8} + 2.36 \times 10^{-10} \cdot T - 5.22 \times 10^{-12} \cdot T^2 \\
A_2 &= 5.62 \times 10^{-8} + 7.52 \times 10^{-10} \cdot T \\
A_3 &= [55.9 - 2.37 \cdot T + 4.77 \times 10^{-2} \cdot T^2 - 3.48 \times 10^{-4} \cdot T^3] \cdot 10^{-15} \\
f_1 &= 1.32 \times 10^3 (T + 273.1) e^{\frac{-1700}{T+273.1}} \\
f_2 &= 1.55 \times 10^7 (T + 273.1) e^{\frac{-3052}{T+273.1}} \\
P_1 &= 1 \\
P_2 &= 1 - 10.3 \times 10^{-4} \cdot P + 3.7 \times 10^{-7} \cdot P^2 \\
P_3 &= 1 - 3.84 \times 10^{-4} \cdot P + 7.57 \times 10^{-8} \cdot P^2
\end{aligned}$$

Table III
AINSLIE & MCCOLM MODEL'S COEFFICIENTS

$$\begin{aligned}
f_1 &= 0.78 \sqrt{\frac{S}{35}} e^{\frac{T}{26}} \\
f_2 &= 42 e^{\frac{T}{17}}
\end{aligned}$$

of attenuation of absorption is frequency dependent since at higher frequencies more energy is absorbed. There are several equations describing the processes of acoustic absorption in seawater which have laid the foundation for current knowledge. Each of these equations has over time improved the applicability and accuracy of mathematically predicting the absorption of sound in sea water. Each mathematical model obtains the signal absorption coefficient according to environmental and signal characteristics. The attenuation by absorption models considered for inclusion into the AquaTools simulation toolkit are discussed here.

1) Thorp Model: The Thorp model [7] shown below, in Equation 3, provides the absorption coefficient in dB/km:

$$10 \log \alpha = \frac{0.1 f^2}{1 + f^2} + \frac{40 f^2}{4100 + f^2} + 2.75 \times 10^{-4} \cdot f^2 + 0.003 \quad (3)$$

This model is very simple to implement and only depends on the signal frequency. It is designed to be most accurate for a temperature of $4°$C and a depth of approximately 1000m.

2) Fisher & Simmons Model: The Fisher & Simmons model is one of the most commonly used and referenced models [11], [12], [13]. It takes into account the effect of temperature and depth, while also introducing the effects of relaxation frequencies caused by boric acid and magnesium sulphate. The result obtained in dB/km from this model can be obtained from:

$$10 \log \alpha = A_1 P_1 \frac{f_1 f^2}{f_1^2 + f^2} + A_2 P_2 \frac{f_2 f^2}{f_2^2 + f^2} + A_3 P_3 f^2 \quad (4)$$

The coefficients A_1, A_2, A_3, P_1, P_2, P_3, f_1 and f_2 in Equation 4, can be obtained from Table II, where T is the temperature in °C and P is the pressure in atmospheres. The Fisher & Simmons model operates under the restriction that the depth cannot be greater than 8 km and the salinity has been restricted to a value of 35 ppt, while the pH value has been fixed at 8. The ability to model effects of depth and temperature, in addition to distance and frequency, makes the Fisher & Simmons model attractive for implementation in the simulator.

3) Ainslie & McColm Model: The Ainslie & McColm equation proposes some extra relaxations and simplifications in comparison to the Fisher & Simmons model. The attenuation coefficient in dB/km may be obtained from:

$$\begin{aligned}
10 \log \alpha = \; & 0.106 \frac{f_1 f^2}{f_1^2 + f^2} e^{\frac{pH - 8}{0.56}} \\
& + 0.52 \left(1 + \frac{T}{43}\right) \left(\frac{S}{35}\right) \frac{f_2 f^2}{f_2^2 + f^2} e^{\frac{-D}{6}} \\
& + 4.9 \times 10^{-4} f^2 e^{-\left(\frac{T}{27} + \frac{D}{17}\right)} \quad (5)
\end{aligned}$$

The coefficients for Equation 5 may be obtained from Table III, where pH is the acidity of water, S is the salinity in parts per trillion, T is the temperature in °C and D is the depth in meters. The Ainslie & McColm model, in addition to depth and temperature, also takes into account the effects of the acidity of sea water. This ability to model a wider range of parameters increases the applicability of this equation and the possibility of yielding more accurate results as well. As such, this model was chosen for implementation within the AquaTools simulation toolkit as well.

D. Ambient Noise Model

Ambient noise in the ocean can be described as Gaussian and having a continuous power spectral density (p.s.d.). The four most prominent sources for ambient noise are the turbulence, shipping, wind driven waves and thermal noise. The p.s.d. in dB re μPa per Hz for each of these is given by the formulae [14] shown below:

$$10 \log N_t(f) = 17 - 30 \log f \quad (6)$$

$$10 \log N_s(f) = 40 + 20(s - 0.5) + 26 \log f - 60 \log(f + 0.03) \quad (7)$$

$$10 \log N_w(f) = 50 + 7.5 w^{\frac{1}{2}} + 20 \log f - 40 \log(f + 0.4) \quad (8)$$

$$10 \log N_{th}(f) = -15 + 20 \log f \quad (9)$$

The ambient noise in the ocean is colored and hence different factors have pronounced effects in specific frequency ranges. In the noise model equations utilized for this study the colored effect of noise is represented by N_t as the turbulence noise, N_s as the shipping noise (with s as the shipping factor which lies between 0 and 1), N_w as the wind driven wave noise (with w as the wind speed in m/s) and N_{th} as the thermal noise.

Turbulence noise influences only the very low frequency region, $f < 10$ Hz. Noise caused by distant shipping is dominant in the frequency region 10 Hz -100 Hz. Surface motion, caused by wind-driven waves is the major factor contributing to the noise in the frequency region 100 Hz - 100 kHz (which is the operating region used by the majority of acoustic systems). Finally, thermal noise becomes dominant for $f > 100$ kHz.

The overall noise p.s.d. may be obtained in μPa from:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \tag{10}$$

The noise p.s.d. may be used along with the signal attenuation to arrive at values that characterize the channel performance.

IV. CHANNEL CHARACTERIZATION MODEL

The underwater acoustic channel is locally time varying, there exists no single character for the channel that could be globally used as a model. This makes it important to characterize the underwater acoustic communication channel in order to determine the effects of local environmental phenomenon on achievable performance. This performance of the channel can be characterized by properties that include signal-to-noise ratio (SNR), optimal transmission frequencies and the capacity bound.

A. Signal-to-noise ratio

Using knowledge of the signal attenuation $A(l, f)$ and the noise p.s.d., $N(f)$, the SNR observed at the receiver may be calculated in μPa re dB per Hz from the following equation:

$$SNR(l, f) = \frac{P}{A(l, f)N(f)\Delta f} \tag{11}$$

where $SNR(l, f)$ is the SNR over a distance l and transmission center frequency f, P is the signal power and Δf represents the receiver noise bandwidth. In case the transmission bandwidth, $B(l)$, over a distance l is known along with the transmission power $P(l)$, then Equation 11 can be rewritten as:

$$SNR(l, B(l)) = \frac{\int_{B(l)} P(l)A^{-1}(l, f)df}{\int_{B(l)} N(f)df} \tag{12}$$

The attenuation model choice also adds a dependence upon depth, temperature, salinity and acidity of the specific oceanic region that is of interest, for the SNR.

B. Optimal Transmission Frequencies

The attenuation-noise (AN) factor, given by $\frac{1}{A(l,f)N(f)}$ from Equation 11, provides the frequency dependent part of the SNR. By close analysis of this relationship, it can also be determined that for each transmission distance l there exists an optimal frequency at which the maximal narrow-band SNR is obtained. Since the SNR is inversely proportional to the AN factor, the optimal frequency is that for which the value of 1/AN (represented in dB re μPa per Hz) is the highest over the combination of a certain distance, $f_o(l)$.

While this optimal transmission frequency is not helpful in simulating specific modems, it can be valuable in determining the appropriate modem or frequency to use in a particular scenario. Using these optimal frequencies one may choose a transmission bandwidth around $f_o(l)$ and adjust the transmission power to meet requirements of a desired SNR level.

C. Channel Capacity

Channel capacity is a good metric since it governs many aspects of network design and can lead to significant changes in topologies, protocols and access schemes utilized in order to maximize the overall throughput. As per the Shannon theorem the channel capacity C, i.e. the theoretical upper bound on data that can be sent with a signal power of S subject to additive white Gaussian noise is:

$$C = B \log_2 \left(1 + \frac{S}{N}\right) \tag{13}$$

where B is the channel bandwidth in Hz and $\frac{S}{N}$ represent the SNR. The basic Shannon relationship shown in Equation 13 can be extended to be applicable in cases where the noise is dependent on frequency to take the form of:

$$C = \int_B \log_2 \left(1 + \frac{S(f)}{N(f)}\right) df \tag{14}$$

If we assume a time-invariant channel for a certain interval of time along with Gaussian noise then we can obtain the total capacity by dividing the total bandwidth into multiple narrow sub-bands and summing their individual capacities. In this case each sub-band has a width of a small Δf which is centered around the transmission frequency, i.e. the bandwidth. We may, as such, extend Equation 14 to obtain the channel capacity over a distance l from:

$$C(l) = \int_B \log_2 \left(1 + \frac{P(l)}{A(l, f)N(f)B(l)}\right) df \tag{15}$$

The choice of the underlying absorption coefficient model imposes a dependence of the capacity on depth, temperature, salinity and acidity as well.

V. THE AQUATOOLS SIMULATION TOOLKIT

Network performance is not only dependent upon the physical characteristics of the underwater acoustic channel. In order to provide an overall performance analysis it is important to also evaluate the network statistics which result from media access control schemes, routing protocols, modulation schemes and other networking layers. It is important to build a software infrastructure that takes into account a complete acoustic propagation and channel model and implements them such that it can provide details on achievable data rates, performance of routing protocols, delivery ratio of packets and other characteristics.

The ns2 simulator, which is a popular tool used for simulating network performance, provides an excellent basis to develop a software implementation for simulating the underwater acoustic channel. As such, the AquaTools simulation toolkit was developed to work using the ns2 simulator. The ns2 simulator divides the channel and physical layer functions and characteristics into four components, namely Propagation, Channel, Physical, and Modulation. AquaTools provides implementations appropriate to the underwater acoustic channel for these components.

Figure 1 depicts this division, highlighting the characteristics provided by each individual component and the interaction between them. The propagation component contains most of the characteristics of the signal propagation through the medium (including attenuation) and of the ambient noise. In addition to distance-dependent attenuation, in underwater channels the signal fading is also affected by the orientation of the link. This directivity is also modeled in the propagation component. The characteristics exported to other components of the ns2 model include the calculation of the received bandwidth, signal strength and the interference range of a signal.

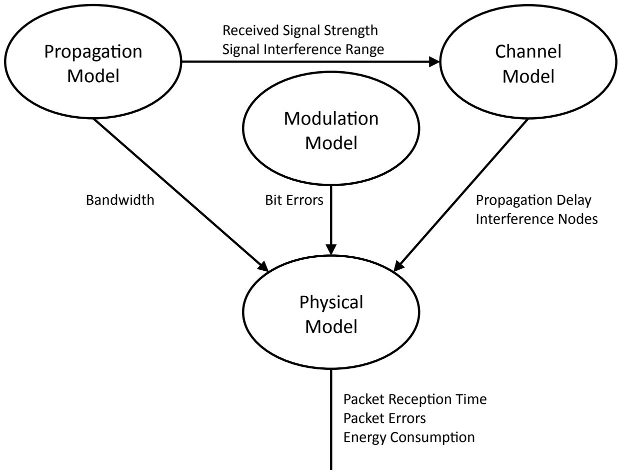


Figure 1. The ns2 functional model. Outputs provided by each module are shown next to the arrows connecting the nodes within the graph.

The primary function of the channel model is to handle propagation delay calculations and to make use of the functions from the propagation model. The physical model tracks energy consumption metrics and also calculates the transmission times. Unlike in radio models, where the bandwidth is assumed to be constant regardless of the transmitter-receiver distance and therefore no information for other layers is required, in an underwater network the link bandwidth does depend on the link length, depth, ambient temperature, salinity and acidity, and as such, bandwidth information from the propagation layer of ns2 must be exposed to other components, i.e. the physical model.

Finally, the physical model calls the modulation model to calculate bit error probabilities given a received signal strength, modulation scheme and level of noise. The AquaTools toolkit uses dB re μPa as the unit of sound energy throughout the implementation since this a typical unit of signal strength used in acoustic communications. Accordingly, all quantities expressed here are in this unit and all tunable parameters (for example, transmit power) are also given in dB re μPa.

A. Underwater Propagation Model

In ns2, propagation models are responsible for calculating the signal-to-noise ratio at the receiver after attenuation and ambient noise are taken into account, as well as the interference range of a signal.

The AquaTools implementation only requires the user to choose the appropriate underwater propagation model in the simulation script using the names for the respective propagation model based on the namesake of the path loss model that forms its basis:

Propagation/UnderwaterThorp
Propagation/UnderwaterFisherSimmons
Propagation/UnderwaterAinslieMcColm

To calculate the signal-to-noise ratio (SNR) at the receiver and the interference range, both the attenuation of the acoustic signal in water and the ambient noise need to be accounted for. The total attenuation is calculated based on the spreading loss, ambient noise and the signal attenuation. The signal attenuation is obtained from either of the Equations 3, 4 or 5 depending upon the path loss model that is chosen as the basis of the underwater propagation model.

The ambient noise in the underwater environment is contributed majorly by four factors; namely*, turbulence, shipping, wind* and *thermal*. The effect of each of these components of ambient noise in the underwater environment may be obtained from Equations 6, 7, 8 and 9. A total effect of the noise model is arrived at by using Equation 10.

By default the values for the shipping variable, s, and the wind variable, *w*, are set to 0. These simulation variables are bound to script variables called *ship_* and *wind_* respectively and can be set in the usual way with lines such as:

*Propagation/UnderwaterThorp set ship_* ***value***
*Propagation/UnderwaterThorp set wind_* ***value***

where *ship_* can take values from 0 to 1 and *wind_* , which represents wind speed, can take positive values in m/s.

Combining the effects of path loss due to absorption and taking into account the spreading loss as well, the total signal attenuation at the receiver is calculated using Equation 2. The value obtained here is used in the calculation of the SNR at the receiver in combination with the ambient noise calculation. This calculation is done by a function that overloads the Pr function of ns2 and uses a form of Equation 12 to arrive at a result of the received power.

The ns2 simulator has a node class that keeps information specific to each node in the simulation, including location coordinates (x, y, z) and transmit power settings. The node class also has a number of member functions used to access information about the nodes. The Pr function takes pointers to the two communicating nodes and is used by the channel module in the calculation of packet loss probability. To find the attenuation for a given transmission between two nodes, the center frequency for the transmission must be found. The center frequency and bandwidth of the modem being modeled may be set up in the simulation script by setting values for the appropriate variables:

*Propagation/UnderwaterThorp set centerFreq_* ***value***
*Propagation/UnderwaterThorp set bandwidth_* ***value***

In case a value for the center frequency and bandwidth is not provided in the simulation script, the frequency that exhibits the best propagation conditions for the transmission distance between the communicating nodes, i.e. the optimal frequency obtained via Equation 11, is chosen. A 3 dB wide transmission band is also assumed around this transmission frequency. The distance between nodes is calculated by the propagation model in order to obtain the center frequency, and thereby the received signal strength. The AN factor for every possible transmission frequency is then calculated and the frequency with the lowest AN factor (largest value of the AN variable) is tracked. Finally, the AN factor that corresponds to that frequency is combined with the transmitted power to calculate the SNR at the receiver and is taken to be equal across the the frequency spectrum.

The ns2 propagation model is also expected to define the radius in which a transmission needs to be considered for interference with other nodes' transmissions. The function *getDist()* takes a threshold received power level, the transmit power level and the frequency at which the signal was sent, and returns the largest distance that a node should be from the transmitter and still be considered interfered with by its transmission.

Essentially, this function finds the target attenuation that is needed to result in a received signal strength so low that it does not need to be considered for interference calculations. It then iteratively calculates the attenuation at distances starting at one meter until it finds the target factor. This function is only accurate to the closest meter.

The results obtained from the propagation model are used by the channel model to make collision and transmission error decisions. As such, it does not need to calculate propagation delay or bandwidth. However, these functions are implemented in the channel model, which is described in detail further.

B. Underwater Channel Model

The channel model in ns2 maintains the node lists used to calculate neighbor sets, collisions and etc. It is additionally responsible for calculating propagation delays. Essentially, the physical layer calls the *sendUp()* function with a packet and a pointer to itself, and the channel model calculates neighbors that may be affected by the transmission as well as propagation delays and returns this information.

Aside from calling the appropriate propagation model functions, such as *getDist()*, the ns2 channel model has to implement the propagation delay model as well, which is somewhat complex due to the dependency of the speed of sound on the depth of the water. In addition to the depth in the water, the propagation speed also depends on the temperature and salinity of the water, which in turn depend on the depth through a non-linear relationship.

In order to provide a realistic simulation, the global average observed thermocline and halocline [6] are modelled within the AquaTools implementation as the functions *getTemperature()* and *getSalinity()*, which provide the temperature and salinity, respectively, as a value which is proportional to the current depth.

With these values obtained the speed of sound can be modelled easily using the relationship defined in Equation 1. There are only five known ocean zones where the speed of sound can be expressed as a linear relationship [4], and only for these zones the simulator would not provide results which should be closely matched to reality.

In order to calculate the propagation delay, the *getPDelay()* function takes segments of distance traveled depending on the nodes' depth and calculates the time taken to traverse the distance segment. When all of the segments of the path have been added together, the total propagation delay is returned. A function *SetDistVar()* takes the current values of the highest and lowest depth (z-variables) and returns the distance traveled in the next segment of linear temperature change, the average temperature in that zone and the updated values for the z-variables.

To use the underwater channel model, it is only necessary to choose it in the simulation script using the name, *Channel/UnderwaterChannel*.

There is only one variable in the channel model that may be set by the user in order to override the *getSalinity()* function. The salinity value for the water used in the propagation delay calculation can be set to some other value than the one returned by *getSalinity()* as shown below:

*Channel/UnderwaterChannel set salinity_* ***value***

The physical layer model uses information from both the channel model and the propagation model to calculate transmission times, total delays, and the success or failure of packet reception. The physical layer model is described in detail further.

C. Underwater Physical Layer Model

The physical layer model of ns2 calculates the final statistics used in the simulation with respect to packet reception, including packet error, transmission time and energy consumption. For most of these calculations, calls are made to functions in the channel and propagation models. Additionally, information about energy costs associated with the physical interface are stored and used to calculate residual battery charge and transmission energy costs.

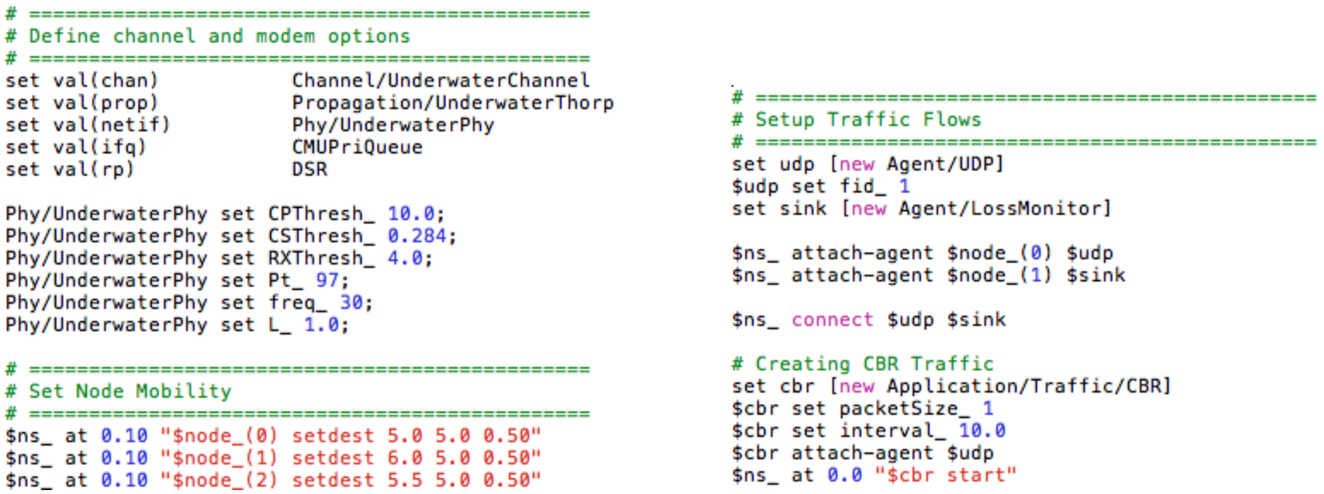
All the specific parameters of interface energy consumption are implemented as variables to be set by the user, since they depend on the specific hardware being modeled. Additionally, the received signal strength threshold and the maximum transmit power levels are interface specific and are also set through variables. The default sets of parameters for the maximum transmit power, receive threshold and the interface energy consumption parameters are set to model the WHOI micromodem [15]. All these parameters can be set up using simple simulation script statements, which are also used by ns2 to set up the interface parameters of wireless radio devices in the 802.11 physical layer model.

To use the underwater physical model, it is only necessary to choose it in the simulation script using the name:

Phy/UnderwaterPhy

To set the maximum transmit power and the receive threshold, set the variables *Pt_* and *Pr_* respectively (units in dB re μPa) as shown below:

*Phy/UnderwaterPhy set Pt_* ***value***
*Phy/UnderwaterPhy set Pr_* ***value***



```
# ===============================================
# Define channel and modem options
# ===============================================
set val(chan)           Channel/UnderwaterChannel
set val(prop)           Propagation/UnderwaterThorp
set val(netif)          Phy/UnderwaterPhy
set val(ifq)            CMUPriQueue
set val(rp)             DSR

Phy/UnderwaterPhy set CPThresh_ 10.0;
Phy/UnderwaterPhy set CSThresh_ 0.284;
Phy/UnderwaterPhy set RXThresh_ 4.0;
Phy/UnderwaterPhy set Pt_ 97;
Phy/UnderwaterPhy set freq_ 30;
Phy/UnderwaterPhy set L_ 1.0;

# ===============================================
# Set Node Mobility
# ===============================================
$ns_ at 0.10 "$node_(0) setdest 5.0 5.0 0.50"
$ns_ at 0.10 "$node_(1) setdest 6.0 5.0 0.50"
$ns_ at 0.10 "$node_(2) setdest 5.5 5.0 0.50"
```

```
# ===============================================
# Setup Traffic Flows
# ===============================================
set udp [new Agent/UDP]
$udp set fid_ 1
set sink [new Agent/LossMonitor]

$ns_ attach-agent $node_(0) $udp
$ns_ attach-agent $node_(1) $sink

$ns_ connect $udp $sink

# Creating CBR Traffic
set cbr [new Application/Traffic/CBR]
$cbr set packetSize_ 1
$cbr set interval_ 10.0
$cbr attach-agent $udp
$ns_ at 0.0 "$cbr start"
```

Figure 2. Simulation script code snippets showing how to set up the channel and modem options, node mobility and also the traffic flows between nodes. Simple code like this can be written to manipulate most aspects of the simulation being performed.

The primary function of interest used in the physical layer is the calculation of the available bandwidth given the distance between the transmitter and receiver, their depths and the ambient environmental conditions. Even though the bandwidth calculation function *getBandwidth()* resides in the propagation model it is described here, since this is the only place where it is used. In case a user specified bandwidth exists, the *getBandwidth()* function returns this. Otherwise, using the distance between the transmitter and receiver, the frequency experiencing the optimum frequency is found. This frequency is used as the center frequency for communication. Then, a 3 dB definition of bandwidth is used to find the edges of the usable frequency band and the appropriate bandwidth is returned.

D. Underwater Modulation Model

The Modulation model in ns2 is responsible for bitrate and bit error calculations based on signal strength and the modulation scheme utilized. The error probability is a function of the SNR. The bitrate and number of bit errors is returned by the modulation model.

No particular modulation scheme has been specifically implemented within the AquaTools simulation toolkit since this was presently beyond the scope of this work. As a result, the AquaTools simulation toolkit currently utilizes the wireless modulation scheme as it is provided by the ns2 distribution in order to perform the bit error calculations. The bitrate utilized is limited to the capacity predicted by an implementation of the Shannon capacity theorem, a mathematical relationship for obtaining which was provided in Equation 15.

Some examples of the code necessary in order to set up a simulation is provided in Figure 2. Similar code segments can also be written in order to modify most of the other aspects of the simulation. In Figure 2, three mobile nodes are being simulated within the underwater acoustic channel using the Thorp attenuation model as the basis. The modem thresholds, transmission power and frequency are defined along with data flow connections set up between the nodes.

VI. TESTING AND RESULTS

The AquaTools simulation toolkit is a generic tool for the underwater acoustics communication community to test and develop underwater acoustic communication systems. Having focus upon two of the largest different user groups for such systems, one networking and the other robotics, this simulation environment provide not only tools that would be very valuable but also those which are within frameworks familiar and often used within these communities. However, before any simulation tool can be utilized to take dependable design decisions, it is necessary to validate the results obtained from the simulator to ensure that they conform to those that are available within published literature or they conform to those expected from numerical models utilized and published in literature.

To validate the implemented underwater models in AquaTools, a number of simulations were run and the resulting values of specific parameters compared with those calculated using analytic models and obtained from published literature, where available. Specifically, it was considered important to validate the major characteristics of the simulator; namely, noise, AN factor, optimal frequency, propagation delay, bandwidth and capacity to ensure there were no errors in the implementations.

Noise calculations are critical for obtaining the important parameters of the propagation and channel modules, such as bandwidth, capacity and SNR. As such, it was considered vital to evaluate the accuracy of the simulator in calculating noise.

The noise calculations obtained from the simulator, as per all the three models, is plotted in Figure 3. Here, the optimal frequency for transmission is used to arrive at an estimate of the ambient noise since the optimal frequency provides the best case performance. The minor differences in the shape of the curves can be attributed towards the fact that each model accounts for different environmental parameters.

While noise is not directly dependent on the transmission distance, verifying this result is necessary since ambient noise is dependent upon the frequency used for transmission and

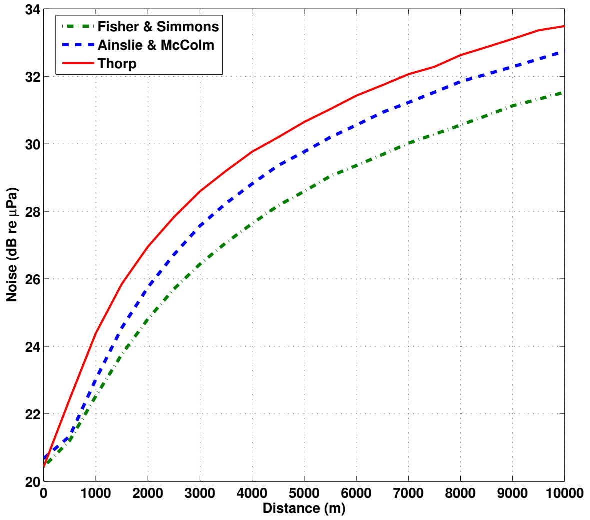


Figure 3. The changing ambient noise as per changing distance which effects the optimal frequency used for noise calculation.

thereby, it indicates whether the optimal frequency predicted by the used models is accurate or not. When compared to the already published results of ambient noise, while using the Thorp mode, within the work performed by Harris et al. [4] we can easily notice that the curves are very similar. While there is no direct comparison available to verify the results from the other two models, the results available are within expectations.

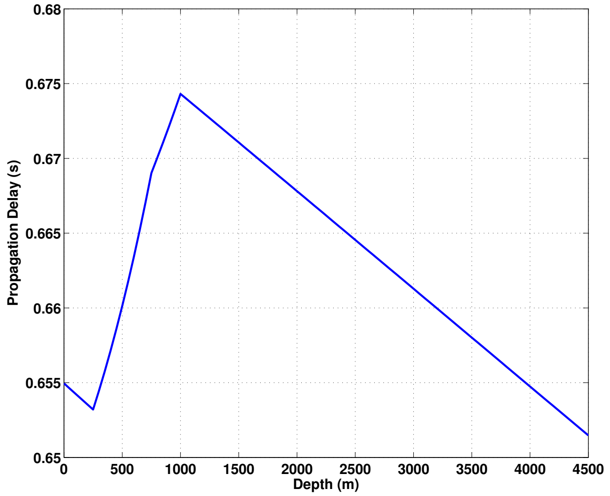


Figure 4. Change in propagation delay with depth of the two nodes. The curve follows a shape similar to that of the sound velocity profile.

Testing the accuracy of propagation delay calculation requires a number of experiments since the result depends on the depth of the communication in the water. The test cases used in the simulator utilized two nodes situated 1 km apart, with one transmitting data to the other. The depth of both the nodes was progressively increased, while maintaining the same depth for both the nodes and keeping the distance between them constant. The resulting values of propagation delay are plotted in Figure 4. The obtained results are within expected parameters since the shape of the propagation delay closely mirrors that of the sound velocity profile, derived from the halocline and thermocline models being utilized.

The SNR is an important value that not only assists in choosing modems, which might function within a specific network design, but also assists in ensuring that nodes in a network are distributed such that a high network efficiency is maintained. The SNR also determines whether the arriving signal at the receiver has a strength strong enough to be accepted or discarded.

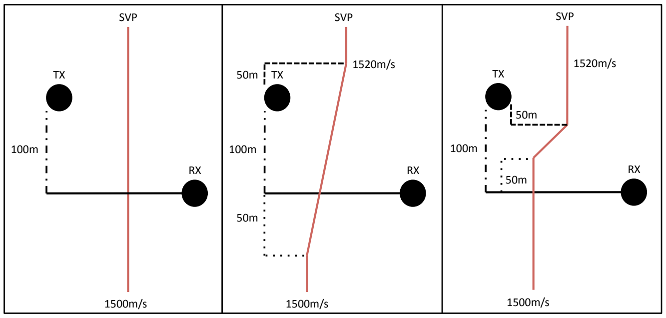


Figure 5. The operational scenario test cases used to perform validation of SNR via AN factor and optimal frequencies.

Three cases for testing were derived from common operational scenarios for underwater acoustic networks. A brief overview of these three scenarios can be found in Figure 5. For testing purposes, the distance between the transmitter and receiver nodes was set to 1 km, 2km and 5 km. By testing for different relative locations of the transmitter and receiver and also accounting for different shapes of the thermocline, which leads to changes in attenuation and other factors, an overview of the behavior of SNR can be obtained.

The authors of [16] point out in their study that SNR is also closely related to the AN factor which assists in deriving the optimal frequency, bandwidth and capacity. Furthermore, the AN factor is a much better method of generally predicting the performance of SNR since the values of SNR are specifically determined by the transmission power of the acoustic signal, whereas the AN factor only depends upon the distance and frequency of transmission; of course, effects of depth, temperature, salinity and acidity are also taken into consideration by choosing the appropriate attenuation model. Harris et al [4] also point out in their work that the shape of the AN factor curve would be similar to that of the SNR; the variation can always be accounted for due to the chosen transmission frequency.

As such, the AN factor was chosen as the benchmark parameter to validate the SNR performance of AquaTools. The results of running experiments with transmission distances of 1 km, 2km and 5 km while using all three models are plotted in Figure 6. The shape of the curves shown here closely mimic those expected from numerical evaluation and also from results published in literature [16], [17].

Finally, the model needs to accurately predict the available

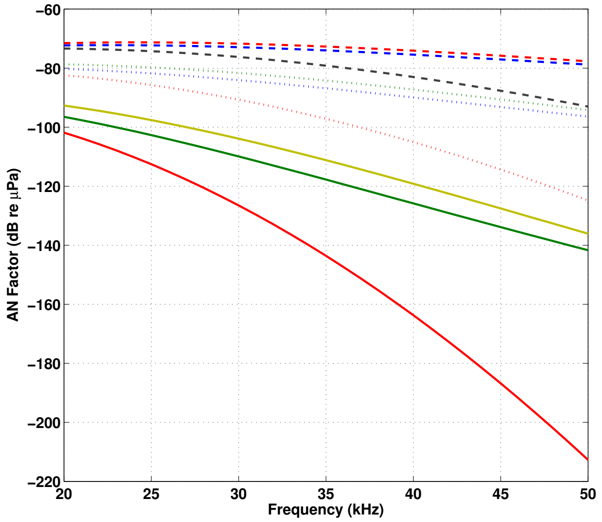


Figure 6. The AN factor's relationship with the transmission frequency being utilized. The close relationship with SNR makes AN factor useful to judge performance. Only common operational frequencies are used here. (Dashed lines - 1km transmission distance, dotted lines - 2km transmission, solid lines - 5km transmission distance; Red - Thorp, Green - Fisher & Simmons, Blue/Gold - Ainslie & McColm)

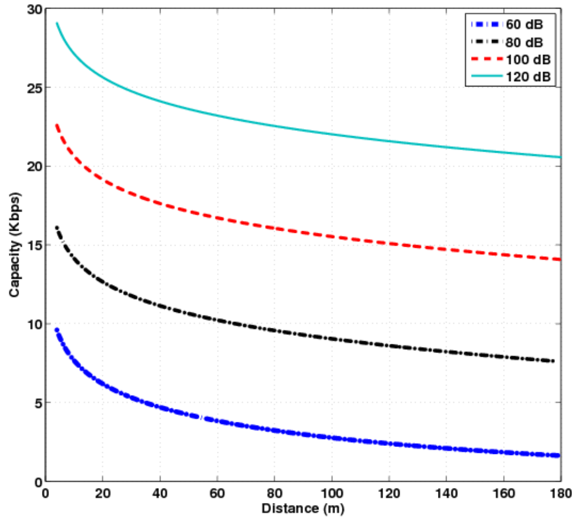


Figure 7. The channel capacity as predicted by the Ainslie & McColm model while the distance between the transmitting and receiving nodes was varied between 4 to 180m and the transmit power is also changed.

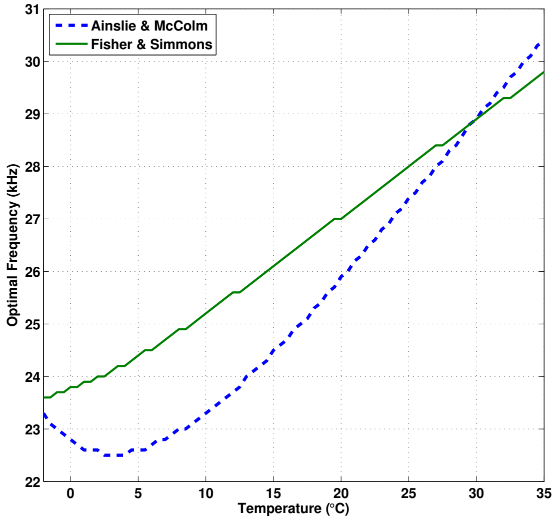


Figure 8. Optimal frequencies with changing ocean temperature. Results obtained with node situated at 1 km depth [6].

bandwidth and the capacity of the channel given the distance between nodes, their depth and also the ambient environmental parameters. The relationship between bandwidth and capacity is a well established one. Higher bandwidth leads to higher capacity; in fact, the relationship between both these operational parameters is so strong that the curve of a plot of each of these would look identical [16]. As such, only channel capacity was plotted from the simulator to test it's accuracy.

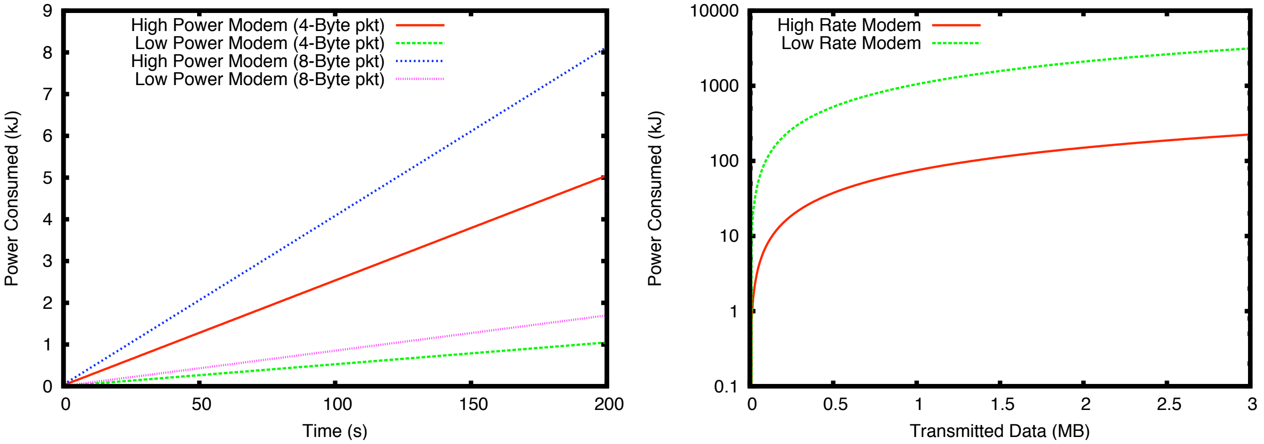
The simulation consisted of two nodes at a depth of 100 m; the WHOI micromodem was modelled as the acoustic modem of choice. Using different transmission powers within the capabilities of the modem, the results were derived by varying the distance between the two nodes between 4 m and 180 m. The results of the experiment can be seen in Figure 7. It is clear from this figure that the capacity reduces logarithmically with distance between the nodes. The plots obtained from AquaTools follow a similar curve to those expected [16], irrespective of the transmission frequency utilized.

The similarity of the results to those expected from numerical evaluation and previously published research shows that results obtained from the AquaTools simulation toolkit are dependable.

Due to the successful validation of AquaTools, it has also been employed in studying the accuracy of different attenuation models [6], developing power management schemes for underwater acoustic network nodes and studying the effects of climate change on the underwater acoustic communication channel. During an analysis of the accuracy of attenuation models a plot of optimal frequencies as predicted by the Fisher & Simmons and Ainslie & McColm based models was obtained. This plot may be seen in Figure 8.

Since most results show that optimal frequency should increase with temperature, it appears that the Ainslie & McColm model has an anomalous performance as compared to that of the Fisher & Simmons model. However, further analysis reveals that at 1 km depth the density of water is actually highest at 4°C, thereby representing a curve that looks almost parabolic [18]. Comparing this behavior of water density with the plot in Figure 8 reveals that the Ainslie & McColm provides results which adhere to this ideology thereby making it the most suitable for simulations.

The goal of the power management scheme study conducted with AquaTools was to determine whether using a single modem or two modems, one low-power and one high-power, was more energy efficient [19]. A network consisting of 8



(a) (b)

Figure 9. Energy consumed by a single node in the network; (a) while transmitting and receiving beacons (b) while transmitting data of varying sizes [19].

static underwater nodes distributed randomly, such that the maximum distance between any node was 1 km, transmitting beacons of 4 and 8 bytes with a time period of one second and 50% duty cycle for neighbor discovery was simulated.

The energy consumed by a single node during neighbor discovery and data transmission are plotted in Figure 9. It becomes clear from these results that a low-power modem is well suited for neighbor discovery while a high power modem should be used for data delivery in order to save maximum energy.

The results obtained from the simulator are useful to develop a power management scheme that uses an adaptive or dual modem scenario. The dependable results obtained from the simulator also make it possible to develop and test MAC and routing protocols as well.

VII. CONCLUSIONS

The AquaTools simulation toolkit provides support for simulating underwater acoustic networks with static or mobile nodes. The availability of three different channel models ensures that simulations can take into account not just transmission frequency but also distance between nodes, depth and ambient temperature, salinity and acidity. Being based on the ns2 simulator, AquaTools provides a flexible scripting interface to set up the simulations. The results obtained from the simulator include detailed packet traces.

A high degree of similarity in the channel characteristics predicted by AquaTools to numerical and published models ensures the reliability of the simulator. The simulator has also been used to conduct a study of different channel models, climate change effects and to develop a power management scheme for underwater networks. The ability to test different protocols and systems with AquaTools makes it a valuable tool in lieu of off-shore testing.

REFERENCES

[1] I. F. Akyildiz, D. Pompili, and T. Melodia, "Challenges for efficient communication in underwater acoustic sensor networks," *SIGBED Rev.*, vol. 1, no. 2, pp. 3–8, 2004.

[2] J. Partan, J. Kurose, and B. N. Levine, "A survey of practical issues in underwater networks," in *WUWNet '06: Proceedings of the 1st ACM international workshop on underwater networks*. New York, NY, USA: ACM, 2006, pp. 17–24.

[3] J.-H. Cui, P. Xie, H. Yan, T. Hu, Z. Shi, Y. Fei, S. Zhou, Z. Zhou, and Z. Peng, "Aqua-sim: An ns-2 based simulator for underwater sensor networks," in *Proc. of IEEE OCEANS '09*, Biloxi, MS, 2009.

[4] A. F. Harris and M. Zorzi, "Modeling the underwater acoustic channel in ns2," in *ValueTools '07*, ICST, Brussels, Belgium, 2007, pp. 1–8.

[5] A. Sehgal, I. Tumar, and J. Schönwälder, "Variability of available capacity due to the effects of depth and temperature in the underwater acoustic communication channel," in *Proc. of IEEE OCEANS '09*, Bremen, May 2009.

[6] A. Sehgal, "Analysis and simulation of the deep sea acoustic channel for sensor networks," Master's thesis, Jacobs University Bremen, Germany, August 2009.

[7] W. H. Thorp, "Analytic Description of the Low-Frequency Attenuation Coefficient," *Acoustical Society of America Journal*, vol. 42, 1967.

[8] E. M. Sozer, M. Stojanovic, and J. G. Proakis, "Design and simulation of an underwater acoustic local area network," in *Proc. Opnetwork 99*, 1999.

[9] K. P. Prasanth, "Modelling and simulation of an underwater acoustic communication channel," Master's thesis, Hochschule Bremen, University of Applied Sciences, August 2004.

[10] K. V. MacKenzie, "Nine-term equation for sound speed in the oceans," *Acoustical Society of America Journal*, vol. 70, pp. 807–812, Sep. 1981.

[11] H. G. Urban, *Handbook of Underwater Acoustic Engineering*. STN ATLAS Elektronik GmbH, November 2002.

[12] F. Fisher and V. Simmons, "Sound absorption in sea water," *The Journal of the Acoustical Society of America*, vol. 62, no. 3, pp. 558–564, 1977.

[13] R. J. Urick, *Principles of Underwater Sound*, 3rd ed. Los Altos, California: Peninsula Publishing, 1983.

[14] R. Coates, *Underwater Acoustic Systems*. Wiley, 1989.

[15] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, and K. Ball, "The whoi micro-modem: An acoustic communications and navigation system for multiple platforms," *http://www.whoi.edu*, 2005.

[16] M. Stojanovic, "On the relationship between capacity and distance in an underwater acoustic communication channel," in *WUWNet '06: Proceedings of the 1st ACM international workshop on underwater networks*. New York, NY, USA: ACM, 2006, pp. 41–47.

[17] A. Caiti, E. Crisostomi, and A. Munafo, "Physical characterization of acoustic communication channel properties in underwater mobile sensor networks," in *Proceedings of International Conference on Sensor Systems and Software*, Pisa, Italy, September 2009.

[18] S. Shell, P. Debenedetti, and A. Panagiotopoulos, "Molecular structural order and anomalies in liquid silica," *Phys. Rev. E Stat. Nonlin. Soft. Matter. Phys*, vol. 66, 2002.

[19] I. Tumar, A. Sehgal, and J. Schönwälder, "Power management for sparse acoustic underwater networks," in *6th IEEE Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON 2009)*, Rome, Italy, June 2009.