An Advanced Channel Framework for Improved Underwater Acoustic Network Simulations

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***Abstract*—Underwater Acoustic Networks (UANs) are an emerging technology that are being used to facilitate new aquatic applications in our water world. This is accomplished by linking underwater sensors, vehicles and devices together using acoustic communication. Network protocol development for UANs often relies on simulations because deploying real systems in the ocean is a resource heavy operation. However, acoustic communication performance is dynamic and dependent upon the environment. Therefore, simulations may not be entirely accurate. In this paper we introduce an advanced channel model that considers environmental impacts and real system characteristics on acoustic communication performance for use in an established open-source simulation environment, *Aqua-Sim*. We provide detailed simulation results and compare the results of our channel model with the existing simulation environment and against the results from a field experiment in the Chesapeake Bay from 2011.**

I. Introduction

The oceans on Earth are estimated to cover 71% of the planet's surface. Yet, more than 95% of the underwater world remains unexplored. Man's inherent desire to explore beyond the known into the unknown has drawn attention to the illusive depths of our oceans. Among exploration, monitoring of oceans for anthropogenic disturbances such as pollution, climate change and severe weather events is rapidly increasing. At the same time, as ocean activities become more mainstream, protection of marine life and the harbors and ports of nations become a bigger necessity. An emerging technology with the potential to enable and extend applications in aqueous environments is an Underwater Acoustic Network (UAN).

UANs make use of sensors, vehicles and other devices to cover large spatial areas of a water environment for monitoring and data acquisition tasks. Additionally, gateway nodes are placed on the water surface to act as a middle man between the operators onshore and devices underwater. They can also be used to collect or route data. An example deployment can be seen in Figure 1. Potential applications of UANs include submarine detection, tsunami monitoring and off-shore structural health monitoring [1]–[4]. The devices and sensors used in UANs are networked together using acoustic communication channels.

Acoustic communication is the ideal communication method for underwater environments as radio waves suffer from high attenuation underwater and optical waves suffer from heavy scattering. However, underwater acoustic communication introduces many challenges that are not as apparent in terrestrial networks. The propagation speed of acoustic signals in water is about 1.5×10^3 m/s, which is five orders of magnitude lower than radio propagation speed in air (3×10^8 m/s). Further, the propagation delay can be dynamic based on the mobility of sensor nodes. Underwater acoustic channels are also plagued by noise generated from ships and sea life, multipath, path loss and Doppler spread. All of these factors attribute to high error probability in the channel. Additionally, the bandwidth is dependent upon both operating frequency and transmission range and is generally limited [5].

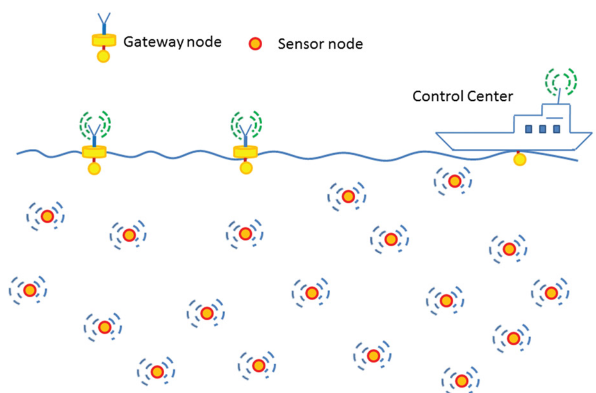

Fig. 1. Example UAN deployment

The aforementioned issues make existing protocols developed for terrestrial networks inadequate for use in UANs. For this reason, many new protocols and entire networking systems have been created. However, these protocols require testing and need to be validated against results from open sea experiments. While many testbed systems have been developed to allow for inexpensive small scale testing, they still require an abundant amount of resources to prepare and perform the experiments. Many researchers have therefore resorted to using simulators to test their new protocols. While this is a viable and necessary step in protocol testing, many underwater network simulators suffer from two problems. The first is that many simulators are not all inclusive, they either focus on the physical communication layer or the networking layers. Additionally, many simulators use a generic underwater acoustic channel model. While this allows for quick and easy testing of protocols, there is no standard agreed upon

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underwater acoustic channel model and therefore the use of the channel model will affect the simulation results. Finally, many simulators are not open source or available for use outside of the research laboratory that developed them, while others require expensive hardware for hardware-in-the-loop emulation.

In this paper we will introduce a communication framework developed for our existing underwater network simulator, *Aqua-Sim* [6], to improve simulation results and accuracy. Currently, *Aqua-Sim* makes use of a generic channel model regardless of scenario or environment. We improve upon this by developing a new communication framework that incorporates three sub-layers, an *environment sub-layer*, a *channel sub-layer* and a *modulation sub-layer*. We provide a new attenuation model used for shallow water channels that incorporates different sediment types and environmental impacts, a noise model, a modulation scheme based on Orthogonal Frequency-Division Multiplexing (OFDM) and two practical real system settings, known as long preamble and low transmission rate. The goal of this work is to show the compounding effect of various factors on the accuracy of simulations and to provide a traditional simulation platform for those who are resource constrained.

The rest of the paper is organized as follows. In Section II we provide related work. Section III presents our proposed architecture. Section IV introduces the specific improvements in each sub-layer. Section V discusses our simulation results and validates them against experimental results acquired from a sea test. In Section VI we provide our conclusions.

II. Related Work

There are a limited number of simulation tools in the research community that have actually been released for public use and frequently maintained. *Aqua-Sim* [6] is one such simulation tool, which focuses on underwater acoustic networking research. It was built upon the existing ns-2 simulator [7] which was developed for terrestrial wireless networks and follows the same object-oriented design style. *Aqua-Sim* is capable of simulating underwater sensor nodes, traffic patterns, acoustic channels and networking protocols. A complete protocol stack has been implemented in which users can test different protocols at each layer such as Medium Access Control (MAC) protocols, routing protocols and reliable data transfer protocols. Figure 2 shows the general architecture of *Aqua-Sim*. Similar simulation environments can be found in [8] and [9].

Underwater acoustic communication is a challenging area in itself and therefore some simulation tools focus strictly on simulating the physical layer. In [10] the authors present a physical layer simulation environment that is driven by standard measurements taken from the environment of interest. This includes items such as impulse response, conductivity, temperature and depth (CTD), noise and transmission loss. This simulator is designed in a modular manner using OMNeT++ 4.0 discrete event simulator [11] and MATLAB. Since this is a physical layer simulator, there is no inclusion of the upper networking layers.

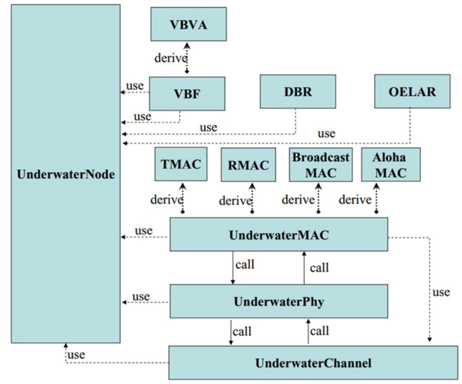

Fig. 2. Aqua-Sim architecture

A more recent direction is towards developing hardware-in-the-loop simulators. Three well known simulators are DESERT [12], SUNSET [13] and Aqua-Net Mate [14]. These simulation tools are also built upon the ns-2 framework, while DESERT and SUNSET also include the addition of the ns2-miracle library. The primary purpose of these tools is to integrate real system hardware into the simulation process to emulate a more accurate environment. In current simulation tools users will have to implement network protocols specific to the simulation environment. Once the user wants to take their protocol to a real sea experiment, they will have to re-implement the protocol again, this time to make sure it works on the real system. These new hardware-in-the-loop simulators seek to combine protocol development into a single effort by combining real hardware with traditional simulations. While these tools include a non-hardware based simulation framework, the emphasis is on the use of real equipment.

III. Architecture

In this section we will introduce our new communication framework for *Aqua-Sim*. We will extend the current physical layer to include three sub-layers: an *environment sub-layer*, a *channel sub-layer* and a *modulation sub-layer*. The proposed protocol stack is shown in Figure 3, where the blue layers are networking related and the yellow layers are the proposed physical layers.

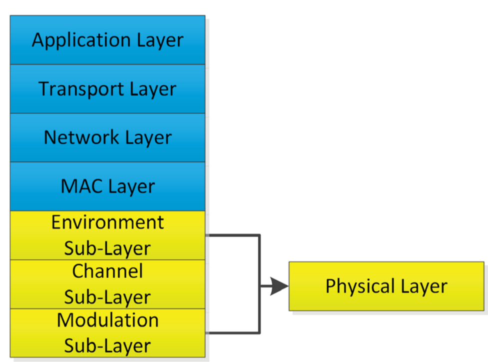

Fig. 3. Proposed protocol stack architecture

The *environment sub-layer* will be responsible for considering the physical factors of the ocean environment and their effects. We will incorporate the refraction of acoustic signals due to various sediment types on the sea floor, such as sand, silt and clay, the depth of the water column and the noise present in the environment from wind and wave effects.

The environment sub-layer ties directly into the *channel sub-layer*. In this sub-layer we will integrate a shallow water attenuation model, known as Roger's Model [15], that considers the sediment types, taken from the environment layer, to produce more realistic transmission loss. We will also consider two practical system parameters, *long preamble* and *low transmission rate* that stem from the use of current commercial acoustic modems.

The output of the channel sub-layer and the environment sub-layer will be used to calculate the SNR, which is used as an input into our modulation sub-layer. The *modulation sub-layer* will then check the SNR against the packet error rate (PER) scheme for OFDM modulation, that is implemented based on a real OFDM acoustic modem, to determine whether or not a packet can be decoded.

The vision for this framework is to consider the physical factors and dynamics while operating in real underwater environments. We wish to take the generalized framework for UAN simulations and make it a more realistic reflection of network operating conditions and signal characteristics.

IV. Framework Details

We have chosen to integrate our advanced channel model in *Aqua-Sim* [6]. The current physical layer model adopted by *Aqua-Sim* is useful but not comprehensively accurate. The standard signal attenuation model used to estimate path loss in the underwater acoustic channel is:

$$A(l, f) = l^k \times 10^{\frac{\alpha(f)}{10} l} \quad (1)$$

where l is the distance between the sender and receiver, f is the frequency of the signal, k is the spreading factor and $\alpha(f)$ is the absorption coefficient. Commonly used values for the spreading factor are $k = 1$ for cylindrical spreading, $k = 1.5$ for practical spreading and $k = 2$ for spherical spreading. The absorption coefficient in *Aqua-Sim* is represented empirically by the use of Thorp's equation which expresses $\alpha(f)$ in dB/km for frequencies in kHz. Thorp's equation for frequencies above a few hundred Hz is as follows:

$$\alpha(f) = 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f} + 2.75 \cdot 10^{-4} f^2 + 0.003 \quad (2)$$

For frequencies below this, Thorp's equation can be used as follows:

$$\alpha(f) = 0.002 + 0.11 \frac{f^2}{1+f^2} + 0.011 f^2 \quad (3)$$

Figure 4 shows the absorption coefficient over varying frequencies. The empirical transmission loss that is currently calculated in *Aqua-Sim* for each k value is shown in Figure 5 using an operating frequency of 17 kHz, the operating frequency of our acoustic modems.

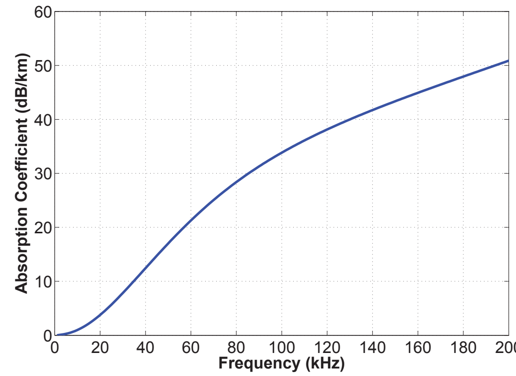

Fig. 4. Absorption coefficient at varying frequencies

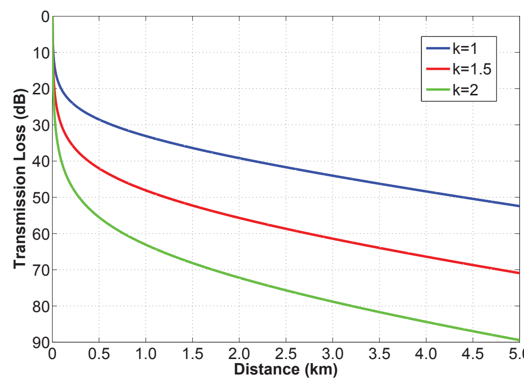

Fig. 5. Aqua-Sim transmission loss

A. Improved Attenuation Model

Shallow water environments are a common deployment area for UANs and often have a dramatic effect on the performance of the acoustic communication. In order to accurately simulate transmission loss in shallow water we make use of Roger's Model [15]. This model provides depth-averaged estimates for range-independent ocean environments and was derived from a physics-based theoretical consideration [16]. The model provides a general equation to describe shallow-water transmission loss curves, which is seen in Equation 4, where R is range and A, B and C are coefficients whose different values can be found in [15].

$$TL = 15 \log_{10} R + AR + B + CR^2 \quad (4)$$

The transmission loss when sound speed decreases with increasing depth, or when $\theta_s > \theta_L$ is as follows:

$$TL = 15 \log_{10} R + 5 \log_{10}(H\beta) + \frac{\beta R \theta_L^2}{4H} - 7.18 + \alpha_w R \quad (5)$$

where R is the range in meters, H is a water column of uniform depth, β is a coefficient determined from the Rayleigh reflection coefficient [15], also known as bottom loss ($dBrad^{-1}$), α_w is the mainstream water attenuation or absorption coefficient of sea water [15], θ_S is the effective angle of the last mode stripped and θ_L is the maximum between the largest grazing angle for an RBR (refracted bottom reflected rays) mode and the cutoff angle of the lowest mode [15]. The spreading loss for mode-stripping regions is represented by the term $15 \log_{10} R$ and after that the spreading loss corresponds to cylindrical spreading, represented by the term $10 \log_{10} R$ (not shown in this paper) [16]. β, the bottom loss, is derived from the theoretical expression for the Rayleigh reflection coefficient for a two-fluid lossy interface, for small grazing angels [16]. For more information on Roger's Model, refer to [15].

In Figure 6 and 7 we compare the transmission loss of Roger's Model with that of the existing attenuation model from Section IV using an operating frequency of 17 kHz, which corresponds to the frequency used by our acoustic modems. For the existing attenuation model we use a value of $k = 1.5$ and for Roger's Model we use a water depth of 100 m. The sediment types are listed in Table I. Roger's Model produces higher transmission loss than that of the previous model. We can observe that the the sediment types partition the results into two groups. Sediment types 1-5, mainly clay and sand mixtures, increase the transmission loss by roughly 10 dB. Sediment types 6-11, courser sand and gravel, are closer to the original attenuation model and are roughly 5 dB higher.

B. Noise Model

In the current version of *Aqua-Sim* there was no inclusion of environmental noise. It is well known that the underwater channel is affected by noise from factors such as bubbles, shipping activity and animal presence [17]. In order to address this issue we have included an existing noise model from [17]. The model considers turbulence, shipping, wind and thermal factors. The input for this model is frequency in kHz, shipping (light to dense) and wind in m/s. It is modeled as a function of frequency in kHz as shown below:

$$\begin{aligned} 10\log NSL_1(f) &= 17 - 30\log(f) \\ 10\log NSL_2(f) &= 40 + 20(s - 0.5) \\ &\quad + 26\log(f) - 60\log(f + 0.03) \\ 10\log NSL_3(f) &= 50 + 7.5w^{1/2} \\ &\quad + 20\log(f) - 40\log(f + 0.4) \\ 10\log NSL_4(f) &= -15 + 20\log(f), \end{aligned} \tag{6}$$

where NSL_1 is turbulence noise, NSL_2 is shipping noise, NSL_3 is wind noise and NSL_4 is thermal noise. Additionally, s is the parameter for shipping activity, w is the parameter for wind activity and f is the operating frequency. The total noise loss in dB is represented as the sum of these factors:

$$N(f) = NSL_1(f) + NSL_2(f) + NSL_3(f) + NSL_4(f) \tag{7}$$

We have also included a representative average based on empirical results in case the specific environment parameters are unknown. This value is represented as 70 dB [18] and is used by default until the user declares the environment parameters, discussed later in Section IV-E.

TABLE I
SEDIMENT TYPES

Sediment Type	Sediment Number
Clay-Silt	1
Clayey Silt	2
Sand-Silt-Clay	3
Silty Sand	4
Fine Sand	5
Silt	6
Medium Sand	7
Medium Coarse Sand	8
Coarse Sand	9
Sand-Gravel	10
Gravel	11

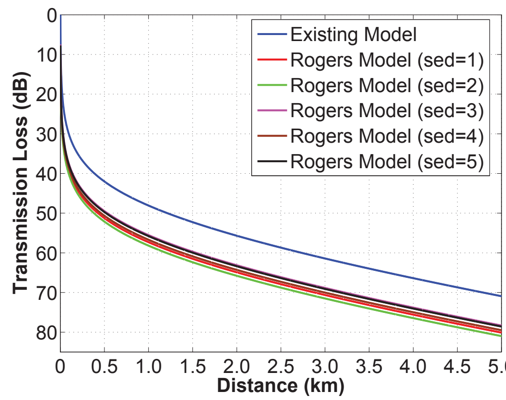

Fig. 6. Transmission loss comparison set 1

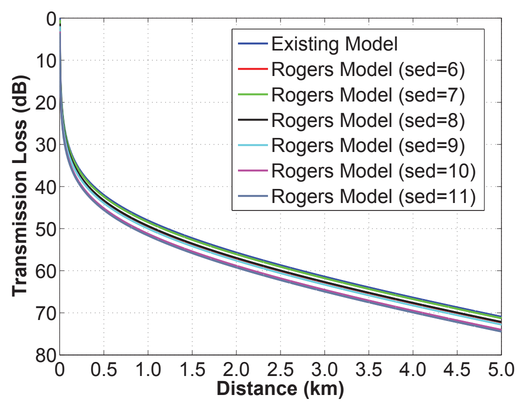

Fig. 7. Transmission loss comparison set 2

C. Modulation

The modulation sub-layer is responsible for representing the communication performance. The existing approach for this layer in *Aqua-Sim* is limited and does not reflect current acoustic modem technology. The current scheme works on a fixed PER. This means that when a packet is received, whether or not it can be decoded is calculated based on a random probability function. Unfortunately, this is not realistic. For our sub-layer we implement an SNR calculation, seen in Equation 8, where P_r is the received power, d is the distance between nodes and f is the operating frequency. We also provide an implementation of OFDM modulation from a real acoustic modem. We make use of an empirical PER model for this scheme that was generated in various real-world testing environments such as pools, lakes and ocean experiments [19].

$$SNR = \frac{P_r}{Attenuation(d, f) \times Noise(f)} \tag{8}$$

For this modulation scheme we offer two options: an ideal channel and a real channel. For the ideal channel, the modulation scheme takes in SNR as an input and will output either a 0 (packet cannot be decoded) or 1 (packet can be decoded). For the real channel, the modulation scheme takes in SNR, Doppler spread and delay spread as inputs, which gives us the PSNR (Peak Signal-to-Noise Ratio), and then outputs the same as the ideal channel. However, the Doppler and delay spread will need to be obtained from real-world experiments from the acoustic modem in order to take advantage of this more realistic scheme. The inputs will be compared against a linear approximation of the PER vs. PSNR or SNR (based on which option is used), which is derived from our acoustic modem in different water environments. This is shown in Figure 8. We can observe that being able to decode or not decode a packet falls within a 3 dB range [19].

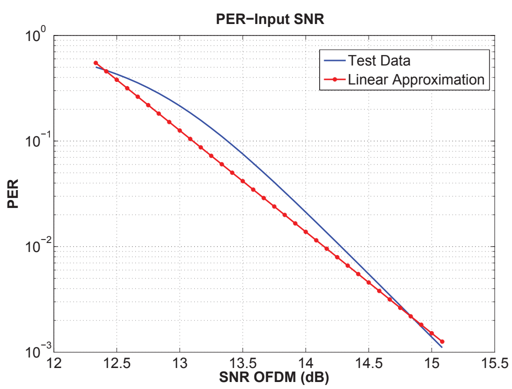

Fig. 8. Linear approximation of PER vs. PSNR

D. Practical Settings

In our previous field experiments we found two system characteristics present in existing commercial modems that significantly degrade network performance. These two characteristics are *long preamble* and *low transmission rate* [20].

In acoustic modems, a preamble sequence is included at the start of a signal for synchronization, signal detection and channel estimation. In terrestrial networks, the preamble is often short and since the transmission rate is much higher, the delay incurred by the preamble is ignored. The preamble durations of common acoustic modems can be seen in Table II. The impact of a long preamble is a higher transmission time with leads to a higher collision probability. Additionally, existing work, such as [21] and [22], claim that transmission rates are about 10 kbps or higher. However, as pointed out in [20], the usable transmission rate is much lower than the theoretical value, especially in shallow water environments with a horizontal channel. The Benthos Modem [23], a commercially available acoustic modem used by many research groups, has a theoretical data rate of up to 15 kbps. However, in order to ensure a low PER in a horizontal channel the data rate is actually much lower. The modem actually transmits at 800 bps and after excluding the overhead for overcoming the multipath effect, the effective transmission rate is only 667 bps [20]. Combining the impact of the long preamble and low transmission rate, we have a significant increase in transmission time and collision probability. These two characteristics have not been considered before in our simulation environment.

TABLE II
PREAMBLE DURATION TIMES OF ACOUSTIC MODEMS

Modem Type	Preamble Duration Time (s)
Teledyne Benthos	1.5
Aqua-SENT OFDM	0.49
WHOI Micro-Modem	0.87

E. Setting Values in Aqua-Sim

In this section we will define how a user can use these new modules in *Aqua-Sim*. In order to make use of certain modules, the user will have to define a few variables in the TCL script, which is where the simulation parameters are defined. These new variables and associated values can be seen in Table III.

TABLE III
TCL VARIABLES

Variable	Value
attenmodel_	0 (or) 1
waterdepth_	User Defined
soundspeeddiff_	User Defined (0 by default)
sedimenttype_	1 - 11
noisemodel_	0 (or) 1
shipping_	0 (or) 1
wind_	0-34
dopplerspread_	User Defined
delayspread_	User Defined

Setting $attenmodel\_$ to 0 will use the existing attenuation model and setting it to 1 will use Roger's Model. If the user wants to use Roger's Model then they will also have to set the $waterdepth\_$ variable, which is user defined based on the deployment scheme (unit is in meters), the $soundspeeddiff\_$ variable, which is user defined and sets the sound speed difference in water (0 by default) and the $sedimenttype\_$ variable, which decides the sediment type that the user wants to use as listed in Table I. The variable $noisemodel\_$ can represent an empirically measured average of 70 dB (set to 0) or realistic conditions (set to 1). If realistic conditions are needed the user will set $shipping\_$ to 0 for light shipping traffic or 1 for dense shipping traffic and $wind\_$ can be set to any value, generally 0 (calm light wind) to 34 (hurricane winds). The $wind\_$ parameter is in units of m/s. For the modulation sub-layer, users can define a Doppler Spread and delay spread value using $dopplerspread\_$ and $delayspread\_$ respectively. These variables can all be set by using the following line in the TCL script:

Phy/UnderwaterPhy **set** *variable value*;

For example, if the user wants to use Roger's Model for their simulation, then in the TCL script they will set the following:

Phy/UnderwaterPhy **set** *atttenmodel_ 1*;
Phy/UnderwaterPhy **set** *waterdepth_ 100*;
Phy/UnderwaterPhy **set** *sedimenttype_ 6*;

V. Framework Evaluation

In this section we show the results of our new framework using various networking protocols and then compare them against the previous results from *Aqua-Sim*. We then compare our simulation results to that of real experiment results from a sea test in 2011 in the Chesapeake Bay near Maryland, USA.

A. Simulation Comparison

For our first comparison we simulated a sparse underwater network using Broadcast MAC and Vector Based Forwarding (VBF) for the routing protocol. Broadcast MAC is a basic MAC protocol that does not have any requirements for acknowledgments or scheduling. When a node has data to send, it sends it. It does not care if other nodes are also forwarding and there is no need for any node to confirm that the packet was received. For VBF, data is routed through a virtual pipe. Every node knows its exact location and the sender specifies a radius for the width of the routing pipe. When the sender sends this message, any node in range of the sender will calculate if they are inside the virtual pipe and forward the packet on. If a node is not in the virtual pipe, it will ignore the packet. A visualization can be seen in Figure 9 where only the nodes in the pipe will forward data packets to the sink.

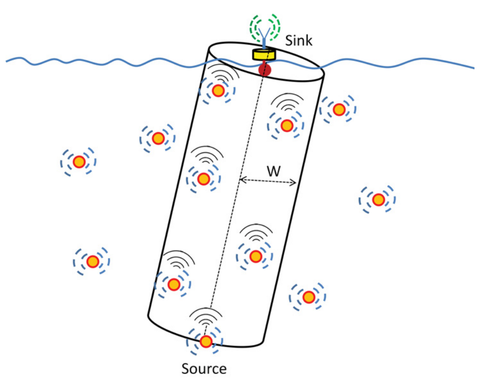

Fig. 9. Depiction of VBF

The results of this simulation can be seen in Figure 10 where we compare the original simulation results with the new simulations results using different environmental settings. The original simulation results can be seen in red. For our framework, in one case, we set the sediment type to Clayey Silt with dense shipping activity and winds of 25 m/s, this corresponds to the blue line. In the second case, we set the sediment type to Clay-Silt and use the standard environmental noise loss, the green line. The third case is using a sediment type of Medium Sand with no shipping and wind activity. For packets being sent at intervals of 1, 2 and 3 seconds we note that given the high traffic rate, many collisions are encountered. In regards to verification, it is beneficial to observe that the new channel model does not affect the protocol dynamics (i.e. all four simulations maintain collisions in this sending interval). This simulation data is an average of 10 runs, a transmission rate of 800 bps, a preamble length of 1.5 seconds and a packet size of 400 bytes.

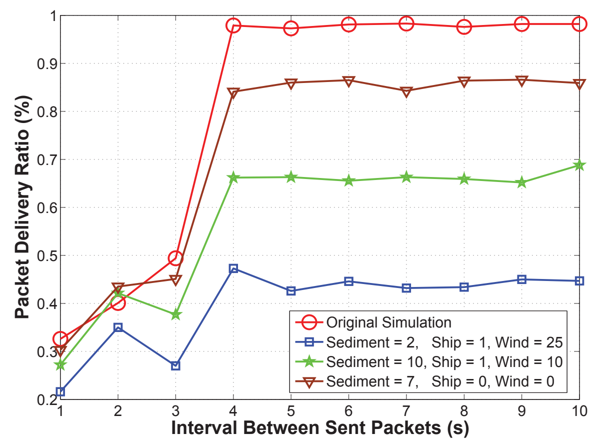

Fig. 10. VBF simulation comparison

B. Chesapeake Bay Field Test

In 2011 we completed an acoustic communication and networking field test in the Chesapeake Bay, Maryland, USA. The experiment consisted of 8 network nodes that were deployed 1 km apart. The deployment area can be seen in Figure 11. The transmitter is node 1 and the receiver is node 8. The data must propagate through all relay nodes before reaching node 8. Since our framework now considers more realistic conditions to accurately reflect the impact of the sea environment on the signal attenuation we compared our simulation results to the results of this field test.

The distribution of sediment in the Chesapeake Bay has been largely studied and therefore we make use of [24], [25] to know the exact sediment types in our area of deployment. Given our deployment area, the sediment make up is largely Clay-Silt (sediment 1) and therefore, we choose this type for our simulation. The Chesapeake Bay has an average depth of 14 m and a maximum depth of 63 m. In our deployment area, nodes were positioned in depths between 16 m and 20 m. The sea conditions varied through out the experiment but we use a wind speed of 8-10 m/s, representative of a fresh breeze. We also set the shipping traffic to dense given that the bay area is fairly active near our deployment area. We use a transmission

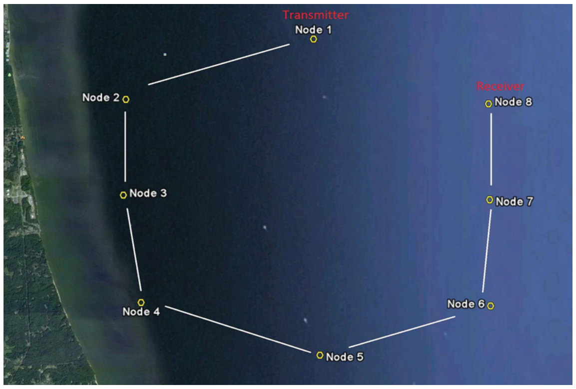

Fig. 11. Chesapeake Bay experiment deployment area

rate of 800 bps, a preamble length of 1.5 seconds and a packet size of 400 bytes. We model traffic using a Poisson traffic generator with varying rates from 0.01 to 0.2.

In Figure 12 we show the throughput of the field experiment in blue, the original simulation environment in red and our improved simulation environment in green. As one can observe, the original simulation environment is not quite accurate when compared with the results from the field experiment. Our improved channel model helps to increase the accuracy of our simulation tool to a much closer result when compared against the field experiment. Additionally, we can observe drops or increases in throughput over the field experiment results, such as at a traffic rate of 0.06 or 0.18. This is a result of an unstable channel during the field experiment. Channel conditions can change frequently and it is difficult to model this in any simulation tool.

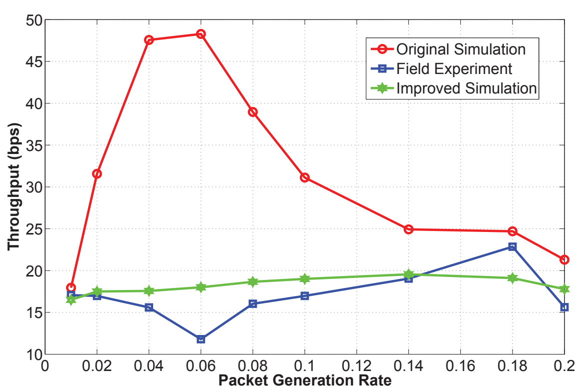

Fig. 12. Field experiment vs. simulation results

C. Discussion

Our new channel framework has improved the accuracy of simulation results but there are a few details that further need to be improved. In many environments, such as the deployment area in our 2011 experiment, there are various sediment types. For instance, some nodes can have a common sediment type while other nodes have a completely different type. In our current framework, the user can only specify one sediment type, which will be used for all nodes. For future work, we will expand this to allow users to specify specific sediment types for each individual node. Another item to note is that environmental conditions cannot be changed once the simulation is running. Therefore, if the user picks an environmental condition of calm wind and no shipping activity, they must keep these parameters throughout the entire simulation. This might effect simulation results when compared to sea experiments. Real sea conditions and environmental effects can change frequently and our current framework cannot account for this issue. A final item to note is that in the 2011 Chesapeake Bay experiment, we used Benthos acoustic modems, which do not use OFDM for modulation. For this reason, our accuracy is slightly affected as we cannot reflect the real modulation scheme used in the 2011 experiment. We look towards future experiments to further verify our new framework with more experimental data.

VI. Conclusions

In this paper we have introduced a new communication framework to represent the physical layer of our *Aqua-Sim* simulator. We have integrated and tested a new attenuation model, a noise model, a modulation scheme based of OFDM acoustic modems and two practical real system characteristics. The proposed communication framework shows an improvement over existing simulation results. We have also compared our new simulation results with the results from a real world sea test to show a much closer analysis to real world experiments.

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