Development of a simple underwater acoustic channel simulator for analysis and prediction of horizontal data telemetry

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ABSTRACT

This study seeks to identify the various mechanisms affecting the performance of horizontal underwater acoustic communication. In order to better understand the impact of oceanographic parameters on acoustic transmission, a simple channel simulator was developed. This was based on the Bellhop propagation model, utilising Gaussian beam tracing. Using a simulated underwater environment and given parameters regarding transmitter and receiver locations, the impulse response was obtained and a subsequent prediction of a received signal was achieved. Using this model, FSK methods of underwater data telemetry were investigated for a variety of scenarios including both deep and shallow water. These predictions were also compared to signals obtained in the field for two different deployments. The results indicated the simulator works effectively to determine areas of more difficult reception for a given environment, despite predicting lower success rates than those found during the trials. It was concluded that additions to environmental data to provide a more realistic simulation may rectify this. In addition, further work in replicating the error correction of the modems will also provide more valuable information about the results observed by the end user. Overall, the simulations worked effectively in providing a simple but effective method of predicting the distortions observed by an acoustic modem receiver.

INTRODUCTION

Background

Underwater acoustic communication is a fast-growing technologying utilised by several industries as both a primary and backup means of sub-sea telemetry. One of the major inhibitors for developing an effective underwater acoustic communication system is the prediction and subsequent adaption to the time-varying physical channel, which can drastically affect its performance.

Problems encountered in such channel include variations in the speed of sound in a particular region of a water column distorting the path of an acoustic signal. As these changes are more significant over depth, long range communications tend to be most affected. Multipath propagation is also an important consideration, particularly in shallow water environments where boundary reflections are more prominent. Arrivals from various paths interfere with each other over short time scales causing constructive and destructive interference, contributing to frequency selective fading. This causes the relative amplitudes of different frequencies to fluctuate and become unpredictable due to time-varying path lengths.

Over long time scales, intersymbol interference becomes a significant problem in systems where it is difficult to determine the shape of the intended packet due to high amplitude reflections. Many of the physical distortions of an acoustic channel depend upon the environment and its boundaries. Seabed roughness and substrate type as well as sea conditions determine the reflectivity of the boundaries in the waveguide and also need to be considered.

Whilst some characteristics are hard to predict to a high level of accuracy, knowing some parameters including rough bathymetry and a general idea of the sound speed profile can still offer great insight into the characteristics of a received signal. By providing predictions of the distortions present within an acoustic channel, the design and testing of acoustic modem protocols becomes more efficient.

Current Progress

The development of channel simulators for underwater communications protocols is commonplace for many acoustic modem manufacturers. Many can be used for higher level simulation and evalulation of acoustic communication such as the implimentation of complex networking protocol. These can dramatically reduce the cost, simplify and importantly speed up testing, becoming integral to the design process. (Otnes, Jenserud et al. 2009).

Use of simulations for lower level characterisation of the physical channel and providing suitable predictions of received waveforms are on-going, with several methods being developed. Some of these operate using statistical models (Zhou and Shim 2008) and others with physical models such as ray tracing (Essebbar, Loubet et al. 1994; Green and Rice 2004; Munoz Gutierrez, Prospero Sanchez et al. 2005). Each of these methods have their own areas of efficiency and subsequent inefficiency for accurate prediction of performance. The design of channel simulators is generally tailored to suit a particular application or protocol due to several factors including the carrier frequencies, modulation types and data rates. This is largely due to the performance dependence on modelled parameters as different regimes may only be more susceptible to problems under certain variations.

Aims and Motivations

The overall aim of the Centre for Marine Science and Technology study is to evaluate the various mechanisms affecting acoustic modem performance, focussing on the time varying natural oceanographic parameters. Whilst much work has been done to collect field data, models have also been utilised to provide a basis for comparison throughout the program. Recently, Bellhop-based modelling methods and data simulation and analysis techniques have been combined to produce a simple channel simulator. This was designed to provide estimates of the complexity of a received signal for any given environment. By using the simulator, future field trials could be planned more effectively to collect reliable data.

THE SIMULATOR

Comparison Basis

The presented channel simulator (Figure 1) was designed to replicate the operation of the AQUAmodem, manufactured by Aquatec Group Limited, UK. The AQUAmodem uses Frequency Shift Keying (FSK) techniques with the implimentation of error correction codes. The modem is designed for horizontal transmission over long ranges in deep water. However, it has also been shown to operate successfully in shallow water.

Data from two trials were used to produce preliminary evaluations of the simulator. The first of these was a deep-water environment involving a linear increase in water depth of approximately 150m to 1000m over a range of 6000m. Modems were located approximately 25m below the sea surface in calm water off the coast of Nice, France. The modems worked effectively over the entire range despite a drop-out at 5000m, possibly caused by multipath interference. (Pusey, Duncan et al. 2009).

A second comparison trial was carried out by CMST off the coast of Western Australia. This was a shallow water deployment in approxmately 30m depth over a range of up to 12000m. Modems communicated at ranges up to 7000m in the extremely challenging environment, involving a sea-bed based receiver and towed transmitter. (Pusey and Duncan 2009).

Data Generation

The first module of the simulator generates an encoded message as expressed by the acoustic transmitter. This already includes the error correction encoding and separation into the FSK sequence. Currently, the hex data sequence can be determined using a random number generator or chosen specifically. The latter is particularly useful when comparing modelled data with results from field experiments. Future work on data generation is planned to include the implementation of error correction codes on a select amount of data, replicating the processing of the modems themselves.

Acoustic Propagation Code

The underwater acoustic propagation code is based on Bellhop, an adaption of ray tracing code (Jenson, Kuperman et al. 2000). Developed by Mike Porter from HLS Laboratories, Bellhop utilises Gaussian beam tracing to model transmission loss throughout the modelled water column. In addition, Bellhop also allows the output of arrival delays and transmission loss for a particular point in the column. The Bellhop code is run as a subroutine of the Centre for Marine Science and Technology's Underwater Acoustic Propgation Modelling Software, AcTUP.

By using the amplitude and delay information from the Bellhop output, the channel simulator compiles an impulse response for a particular receiver position and convolves it with the generated signal in the time domain. The result becomes a simplistic predicted waveform at the receiver, although several aspects of the water column are neglected in the simulator's current form. The first is the addition of noise. At the time of writing, introduction of a noise component into the simulator had not been implemented. However, it is expected that such addition would be relatively trivial, provided the expected noise level spectrum of the area was known.

The Bellhop-based simulator also simplifies the interaction of acoustic signals with boundaries including sea surface and sea bottom reflections. Variations in the surface conditions and sea-bed substrate with range are generally not taken into account in such a system. Unexpected temperature variations and other environmental anomalies throughout a water column may also not be accounted for. However, absolute knowledge of the conditions within a long-range acoustic channel can not be realistically achieved for any model due to the varying nature of the underwater environments in general.

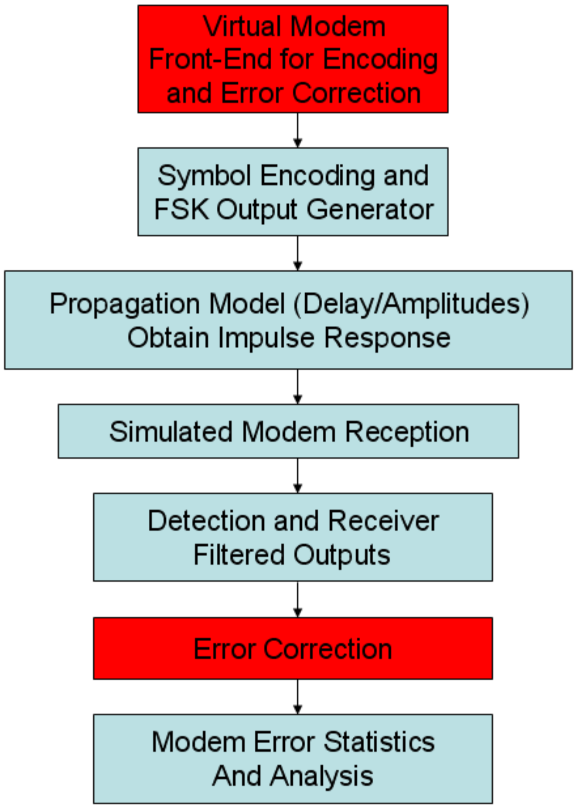

Figure 1. Block diagram of the channel simulator. Items in red are still to be completed.

Data Analysis and Verification

The verification of the simulated received data is performed in a manner similar to the AQUAmodem. The incoming stream is passed through four finite impulse response (FIR) filters to separate out each frequency component. After aligning the first symbol pair, the timed analysis makes a decision for each following bit with a confidence level based upon the distance between the most likely symbol and background.

In the current version of the simulator, the verification is a direct comparison with the symbols used in data generation with no error correction performed. A raw received bit error rate (BER) can then be obtained. The anticipated final model will include implementation of error correction code to better replicate the result observed by the end user.

PRELIMINARY RESULTS

Example Simulation

The simulator was configured to run a sample model for comparison with the data obtained during the trials off the coast of Nice, France. These trials were performed using two vessels in deep water. A diagram depicting ray propagation throughout the environment is shown in Figure 2. This shows the downslope bathymetry and areas of concentrated ray paths. Also shown are downward refracting rays which indicate no direct path is possible for shallow depths at range.

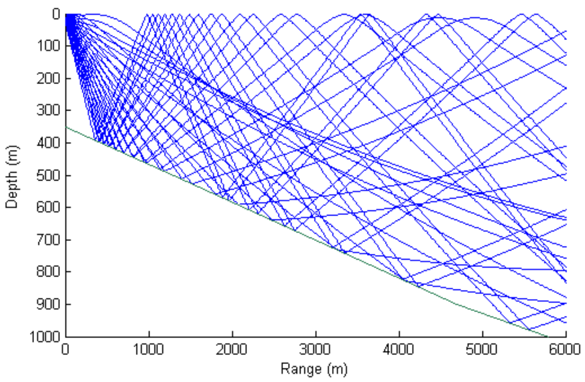

Figure 2. Ray trace diagram showing paths from a 25m source in the declining bathymetry for the Nice simulation.

By extracting the bathymetry from a chart, using documented sound speed profiles and relatively generic bottom conditions, the ray arrivals and transmission loss data were used to compute the simulation. Figure 3 shows an example of the simulated impulse response obtained from the Bellhop code. Here, both the receiver and transmitter are located 25m below the sea surface, approximately 1500m apart. A ray count of 10000 was used.

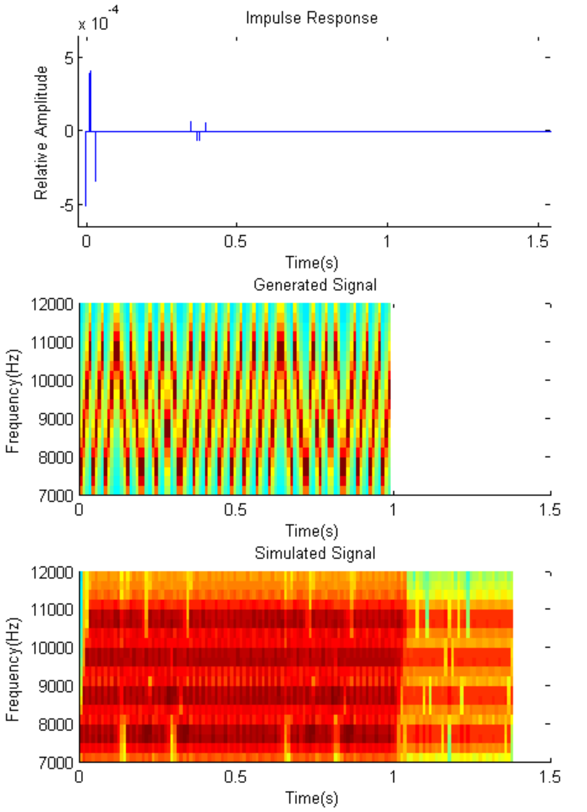

Figure 3. Output visualisation for the channel simulator. Firstly showing the impulse response, generated signal and the simulated result at the receiver.

Also shown is the simulated input to the receiver. The algorithm for detecting and receiving the symbols for comparison uses 4 filtered outputs, f1, f2, f3 and f4. The same example is expressed as four outputs shown in figures 4 and 5. These show the first 8 symbols, which are transmitted in the following sequence:

f1-f2-f3-f4-f1-f2-f3-f4

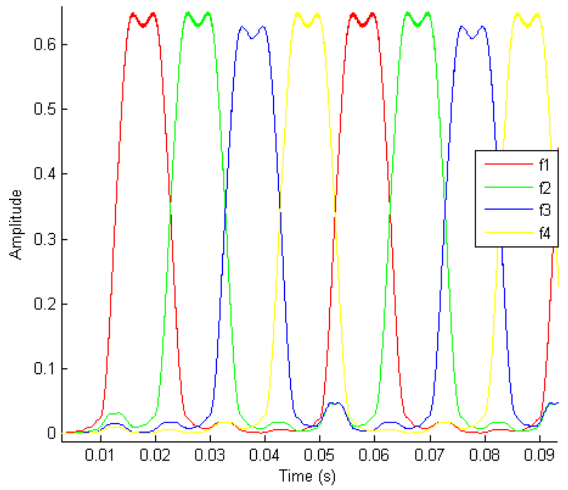

Figure 4. Filtered outputs for analysis of generated signal

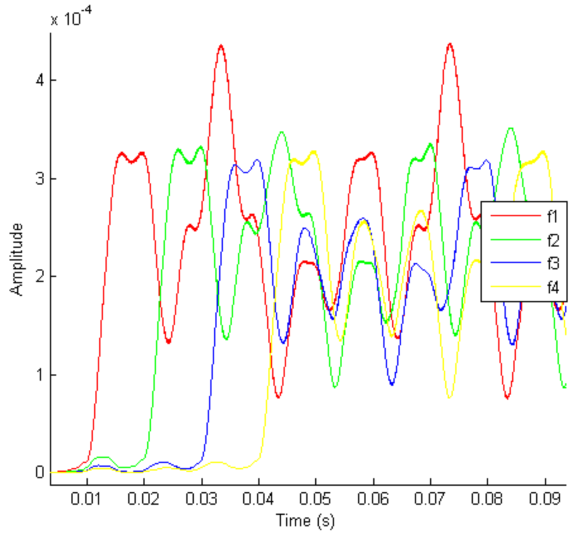

Figure 5. Filtered outputs for analysis of simulated signal for Nice trial

Finally, a comparison is made between the modelled output of the simulation and the original symbol input. Shown in Figure 6, this example demonstrates good correlation at the beginning of the transmission with incorrect decisions later on.

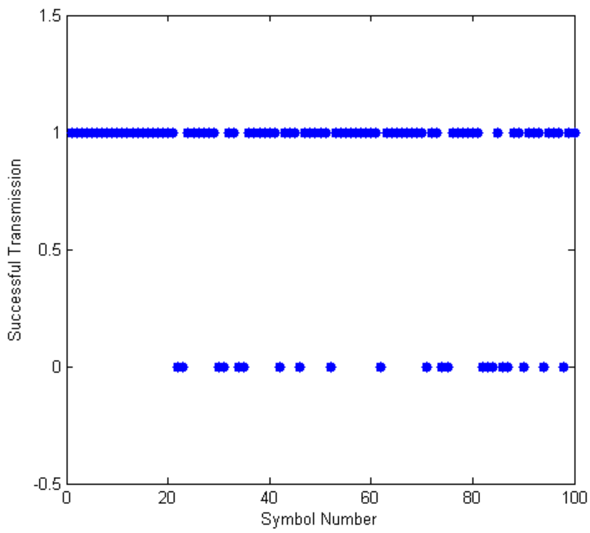

Figure 6. Success rate for example simulation showing failures towards end of packet

The particular example gave a raw bit error rate of 21% which is high considering the relatively short range. Shown later, the overall success of these transmissions become volatile beyond a critical distance, consistent with the introduction of multipath interference, highlighting the difficulties in handling such problems.

Impact of Ray Numbers

The Bellhop propagation model allows for the modification of the number of rays used in the model. This results in the reduction of the size of the Gaussian field for each individual beam. The effect of the number of rays was investigated to determine if it impacted the simulated result. This was done by choosing a controlled model, modifying the ray count and investigating the simulated signal. Figure 7 depicts the zoomed impulse response for 100, 1000 and 10000 rays respectively.

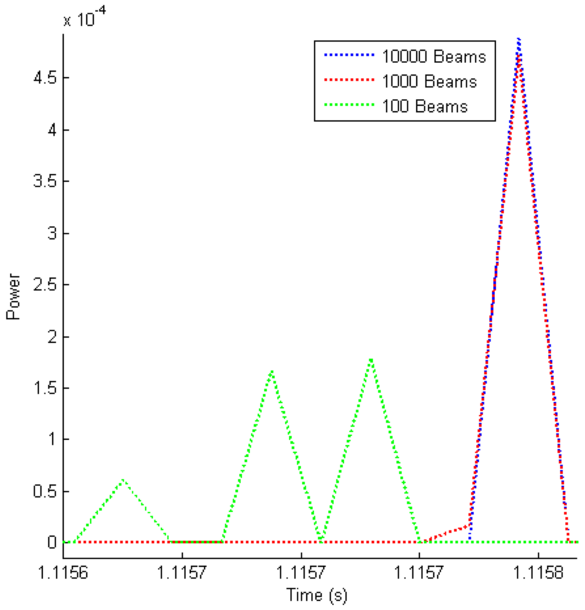

Figure 7. Effect of beam count in propagation model. Less beams result in several arrivals for a single eigenray.

It was determined that very little difference exists between the case of less beams. However, as more rays were used, the number of individual arrivals for a single eigenray was reduced. This results in a more appropriate representation as opposed to several apparent paths for essentially the same arrival. Although the specific number of beams to maximise the efficiency of the single eigenray representation was found to be different for each environment, most of the simulations were performed with 2000 or more Gaussian beams.

Transmission Loss

In order to verify the transmission loss observed at the various points throughout the water column in the simulations, a comparison was made with data obtained using only the model. Bellhop is able to determine the transmission loss independent of creating an amplitude/delay file and this has already been used in previous studies to verify the trends in the comparison trials. In this study, the analysis was performed on simulated data from the receiver to further verify the simulator was providing effective signal strength information.

The simulation for the Nice trial was performed with 20 range increments and compared with experimental data and the Bellhop transmission loss prediction. This can be shown in Figure 8.

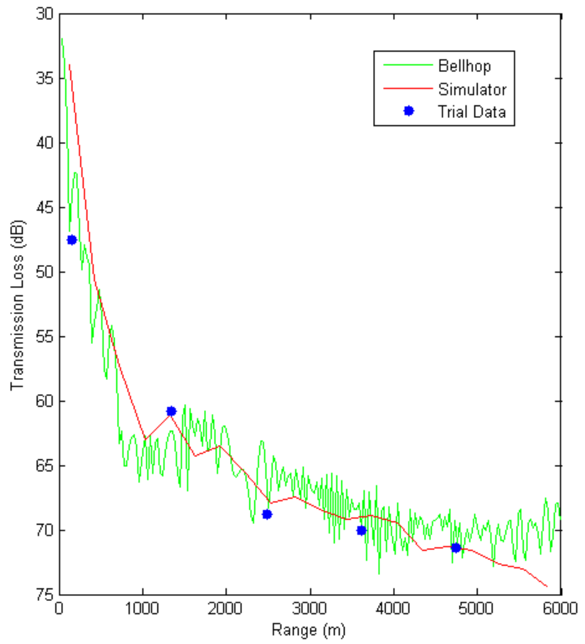

Figure 8. Transmission loss comparison for Nice trial

As shown, there are close similarities with transmission loss indicating the channel simulator had effectively represented the power of an incoming signal. A similar result for the shallow water trials off the coast of Perth can be shown in figure 9. Here, there is a more relaxed correlation between the trial data and that obtained using the model and simulator. Differences with trial data are most likely due to factors not included in the model such as h igher than anticipated sea-bed and sea-surface absorbption at the boundaries. This is consitant with the shallow water case as due to the several reflections involved during transmission.

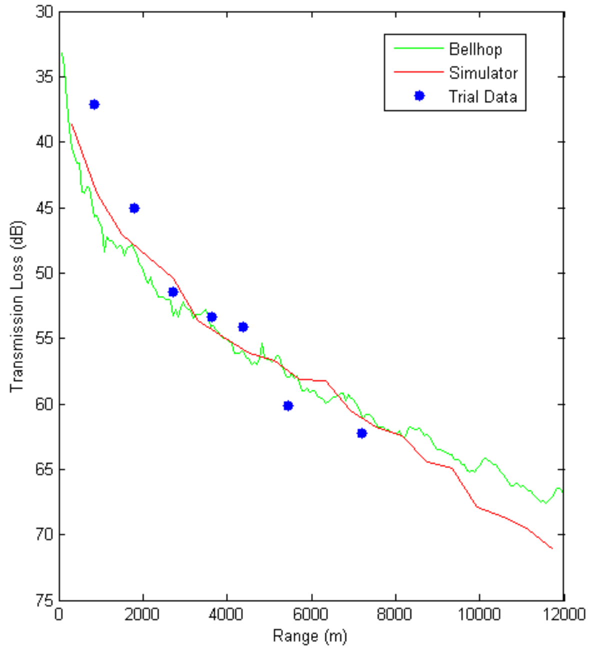

Figure 9. Transmission loss comparison for Perth trial.

However, there are expected to be subtle differences between the simulation and real data as the bellhop model indicates a significant variance with small changes in position. Furthermore, factors such as modem movement need to be accounted for as Doppler spread and frequency selective fading play a vital roll in the ability for the FSK modem to correctly decode a signal.

Multipath Interference

Particularly for shallow water environments, the effects of multipath interference become a large problem for the decoding of underwater acoustic data. Frequency selective fading is caused by constructive and destructive interference of different paths on a shorter time scale, while intersymbol interference is a result of two separate acoustic paths interfearing over longer durations, confusing a receiver as to the intended and correct symbol.

For this analysis, the generator was configured to transmit a wake-up sequence much the same as the AQUAmodem. This involved three short bursts followed by the data stream. Figure 10 demonstrates the sequence generated by the simulator at the transmitter output. During the trials, a short command in much the same shape as that simulated was transmitted.

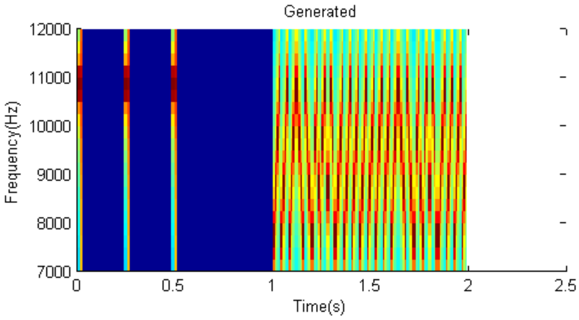

Figure 10. Generated signal showing wakeup sequence and 100 symbols of data.

Two simulations were carried out, one for each of the comparison trials. For the first, the receiver is located in 2000m from the transmitter in the Nice deployment and then again at 5000m range. In the second simulation, the receiver is placed 5000m from the transmitter in 30m of shallow water for comparison with the Perth trial

After passing through the simulator, the signals became expectedly elongated, distorted and evidence of inter-symbol interference becomes clear. Figures 11, 12 and 13 show the result for the respective simulations.

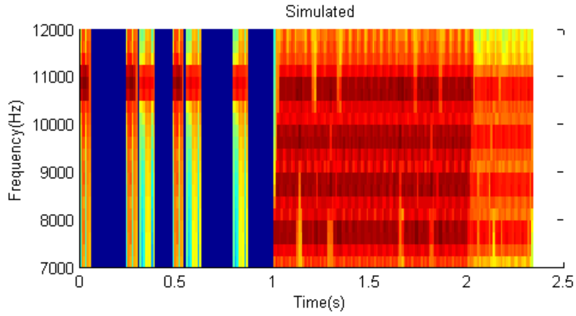

Figure 11. Simulated result of signal for receiver range of 2000m for Nice trials

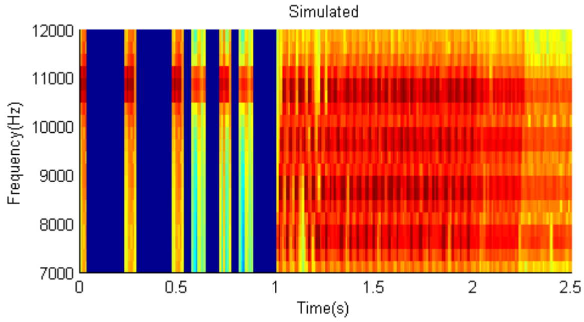

Figure 12. Simulated result of signal for receiver range of 5000m for Nice trials

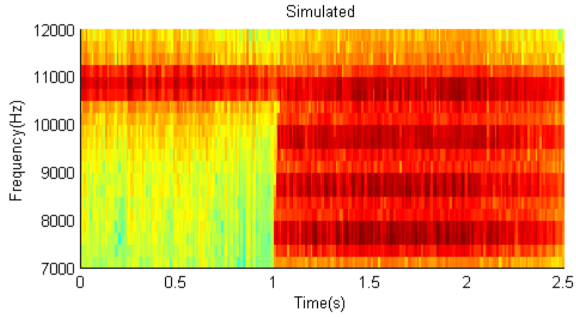

Figure 13. Simulated result of signal for receiver range of 5000m for Perth (shallow) deployment.

An interesting feature of the Nice simulation was the apparent reduction in intersymbol interference at longer ranges. This is explained by ray spread and the increasing depth of the water column. In shallow waters, however, it is shown that intersymbol interference becomes a significant problem.

For the Perth comparison, it was shown that the several reflections occurring within the shallow water column create a distorted waveform for the receiver. The results obtained from these simulations reflect the distortions observed in the trial data. Particularly for FSK based techniques, the intersymbol interference is a large inhibitor of the performance of the trial modems.

Successful Symbol Transmission Rate

Finally, preliminary testing was performed on the response of the modem, given the filtered outputs. By seperating the modems over their trialled ranges, the raw bit error rate was investiaged and compared with the trial results. Figure 14 demonstrates the success rate for the Nice deployment. The simulation was performed for 200 slices of the overall range.

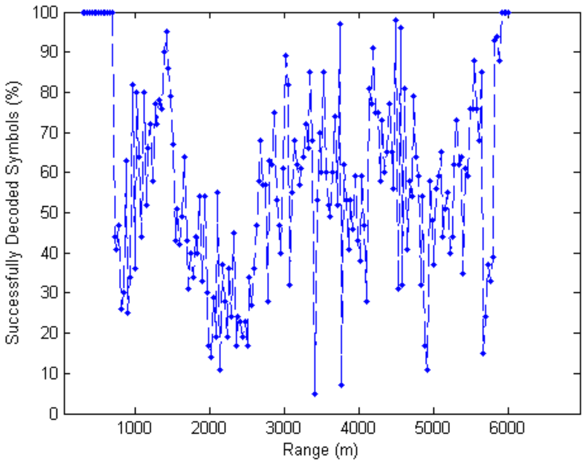

Figure 14. Overall raw symbol success rate for Nice trial over given range.

The results currently deviate significantly from the bit error rates experienced during the field trials, giving rise to the limitations of the system as a method to accurately predict the raw symbol rates due to the trivial design. However, the results were found to correlate with the relative errors with respect to the modem separation. Particularly, close ranges were found to be more promising as predicted by the model, whilst erratic responses were found in later stages. Furthermore, a complete failure of the modems during the trial at an intermediate range can be explained with the simulator demonstrating short range slices of very low success rates at these ranges.

CONCLUSIONS

This study intended to develop and evaluate a simple channel simulator for the better prediction of drop-out zones and areas of effective communication before costly field trials. The results demonstrate an effective method of simulating FSK encoded transmissions in two specific environments, although fully capable of accomodating any two dimensional environment in its current form. Relatively simple to implement, the channel simulator shows good correlation with experimental data when considering the relative performance of the modems. However, quantifying the raw performance of a modem in a given position proved difficult, as in most cases simulations performed much worse than field data indicates.

There are several limitations to the current system, some of which can be rectified with minor changes to the way the models are run. These include the addition of more detail into the bathymetry and environmental information for the Bellhop model such as more detailed sea-bed information. Other more complicated parameters include sea-surface roughness, general acoustic scattering throughout the column and inevitable scattering from objects such as interrogation vessels when using the modems.

Further Work

In addition to factoring in more detail into the model propagation code, other areas will be updated in an effort to produce a reliable indicator of the performance of the FSK based modem discussed here. The first of these will be the implementation of error correction coding much the same as the manufactured modems. This will give a better indication to the actual performance of the device instead of just the raw bit error rates.

Multipath interference shown by the model tends to be significantly larger than that expected and this is most likely due to several factors including subtle movement in the modem positons and lack of parameters including sea bed and sea surface roughness which would result in lower amplitude delayed arrivals. It is expected that more realistic results in this area can be obtained by implementing further detail into the model. With relatively trivial additons to the model, it is anticipated the channel simulator will be an effective tool for the planning of future deployments in the program.

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