Verification of Multi-carrier Modulation Scheme for Shallow Water Acoustic Communication

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Abstract

In the shallow water acoustic channel the simultaneous presence of multi-path effects and Doppler spread causes severe impairments to the transmitted signal. In this paper an experiment is described to verify the performance of a multi-carrier modulation scheme proposed in a previous DTC research project for complex environments. Real physical environments are replicated using a time domain, acoustic communications simulator (ACS). Good results have been obtained in benign and typical environments but further work is required to obtain adequate performance in the most difficult propagation conditions.

Keywords: Multipath, Doppler, Time-spread, Multicarrier, OFDM, Coherence time, Guard-band, PLL, Diversity, TTIB, USB, LSB, DLL, Spread Factor.

Introduction

Acoustic communication in shallow water is very challenging due to combined effects of time spread, arising from the multipath propagation, and the Doppler spread, caused by the medium.

In our previous research [1] a multi-carrier modulation scheme was investigated in which, similarly to the OFDM system, a plurality of narrow band channels, are transmitted. Additionally, CW pilots are placed between the channels to provide local, real-time reference for the demodulation. The symbol rates are scaled to the expected time spread to ensure that the coherence time is longer than the symbol period. Guard-bands around the pilots are dimensioned to provide adequate bandwidth for the expected Doppler spread.

Simulation using a simple channel model [2] indicated that the proposed system could cope well with the simultaneous presence of both multipath propagation and Doppler spread.

In this paper, an experiment is carried out using a high fidelity, time domain, broad band acoustic communications simulator. The paper is organised into 3 sections; first, the simulator is briefly described and the environments are characterised. Next, the transmit waveforms and the receiver architecture is described. Finally the simulation results are presented.

Acoustic Communications Simulator

The Acoustic Communications Simulator (ACS) has been developed by QinetiQ specifically to evaluate performance metrics for acoustic modems under a wide range of operating conditions and environments [3] in a dynamic channel. The model is designed to provide a detailed representation of the multipath, Doppler shift and scattering processes that occur during propagation of an acoustic signal. The model also includes a time-dependent representation of the environment that allows Doppler shifts due to platform motion and moving sea surfaces to be modelled.

The principal functionality of the simulation system is shown in Figure 1.

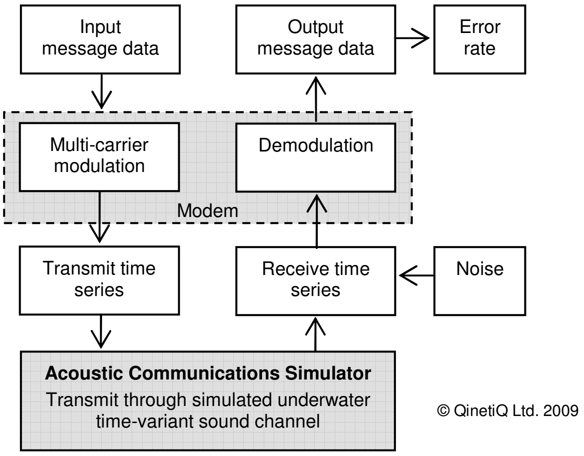

Figure 1: Principal functionality of simulation system

The propagation model has been developed to allow the sea surface to be represented as flat and stationary, time variant sinusoidal or Rayleigh fading.

Attenuation resulting from scattering of energy at the sea surface is represented using the Beckman and Spizzichino model [4]. The ocean bottom is modelled as a three layer system comprising a thin sediment layer, a fluid sediment layer with depth dependent sound speed and attenuation but constant density, and a basement represented solely by a reflection coefficient.

Spreading loss is modelled by calculating the cross sectional area of an infinitesimal ray tube. Absorption is calculated in the water column according to the Francois and Garrison model [5].

ACS is linked to a number of historical databases which provide global and seasonal data for sound speed profiles and wind speeds. ACS is also linked to global databases for bathymetry and seabed parameters.

Sound Channel Simulations

Modelling and simulations are conducted in three environments representing benign, typical and complex propagation conditions. The locations of the environments are Weymouth Bay, the North Atlantic Sea and the Strait of Hormuz.

Weymouth Bay is typical of a shallow water environment (16m water depth) and model predictions are provided to support future practical measurements. The North Atlantic Ocean is a deep water environment (3km to 4km water depth) which provides benign propagation conditions at short ranges. The Strait of Hormuz is a shallow water environment (90m water depth) with complex propagation conditions.

The geometry of the transmitter and receiver is shown in Figure 2. In the simulations the receiver moves directly towards the transmitter at a speed of 5m/s or 10m/s and the range is varied from 0.1km to 10km. The transmitter is at 5m depth in Weymouth Harbour and 20m depth in the North Atlantic and Strait of Hormuz environments. The receiver is at 10m depth in Weymouth Harbour and 30m depth in the North Atlantic and Strait of Hormuz environments.

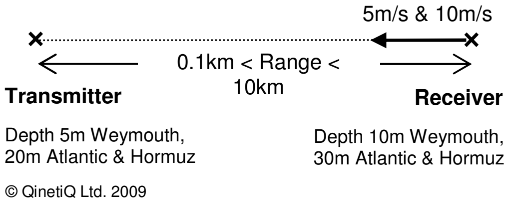

Figure 2: Transmitter and receiver geometry employed in simulations

A modulated time series file of 32 seconds is transmitted in each environment to verify the performance with different surface wave heights, communication ranges, depths and speeds.

Bathymetry and sound speed profiles for the environments are obtained from historical databases except in the Weymouth Bay environment where measured values are used.

Environmental Characterisation

The characteristics of an underwater sound channel depend on many factors including the sound speed profile in the water column, the properties of the seabed and bathymetry, and the wind speed and wave height.

Seasonal variation of the sound speed profile strongly influences the properties of the channel. The sound speed profile in Weymouth Bay is close to iso-velocity during winter and is mildly downwardly refracting near the sea surface in summer (Figure 3).

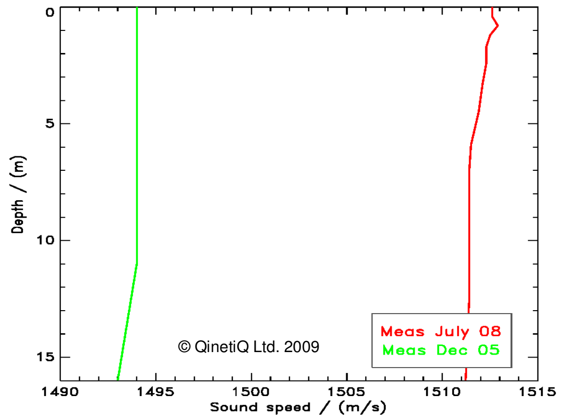

Figure 3: Measured sound speed profile in Weymouth Bay on 21 July 2008

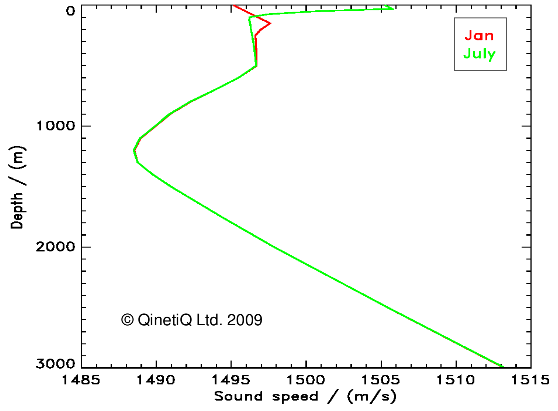

Figure 4: Sound speed profiles in North Atlantic Sea in January and July

The acoustic propagation conditions in the North Atlantic are strongly influenced by seasonal variation of the thermocline (Figure 4). The sound speed profile is upward refracting near the surface resulting in a surface duct which extends to 250m depth in winter and 50m in summer. Below the surface layer, the sound speed profile is downward refracting to 1200m and upward refracting below 1200m where the profile is dominated by pressure.

The sound speed profile in the Strait of Hormuz is mildly upwardly refracting in winter (Figure 5). During the summer months, a shallow surface layer extends to a variable depth of up to 20m, below which the profile is strongly downwardly refracting.

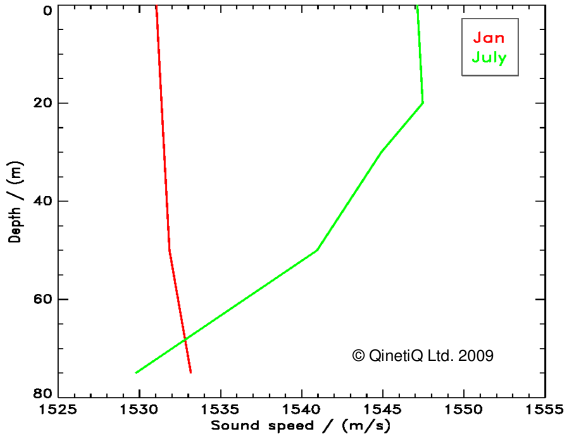

Figure 5: Sound speed profiles in the Strait of Hormuz in January and July

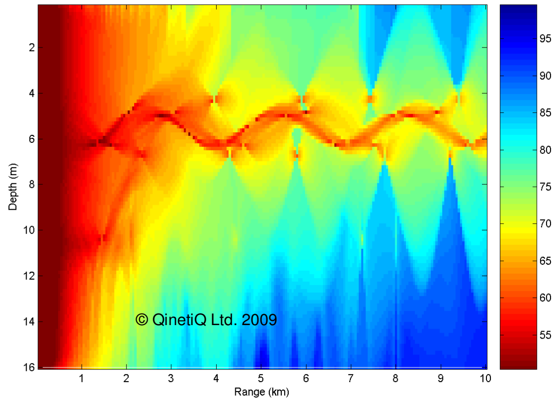

Figure 6: Spreading loss (dB) for source at 5m depth at 11.3kHz in Weymouth Bay in winter

Figures 6 and 7 show the spreading loss in Weymouth Bay in January and July, respectively, for a source at 5m depth. Bathymetry is assumed to be range independent. Energy from the transmitter interacts with both the sea surface and seabed in winter due to the upwardly refracting profile. In comparison, internally reflected energy which does not interact with the sea surface is present in summer due to the downwardly refracting profile. In this environment scattering and channel fading is governed primarily by bottom interactions in summer and by both surface and bottom interactions in winter.

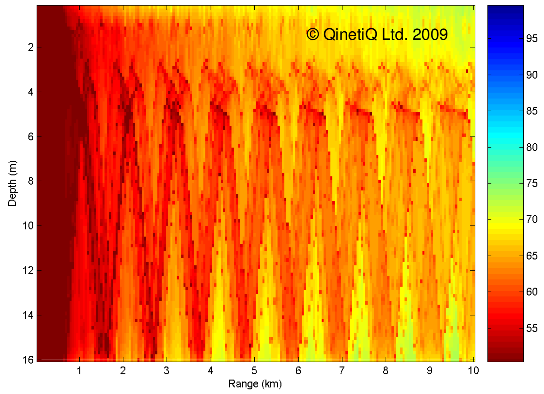

Figure 7: Spreading loss (dB) for source at 5m depth at 11.3kHz in Weymouth Bay in summer

Specific factors, such as time spread, relative power level of Eigen-rays, surface reflected energy, Doppler spread due to moving platform and scattering from moving sea surface are evaluated in the three environments. The dominant eigen-rays which arrive with power levels within 12dB of the maximum eigen-ray are considered.

Example results are shown in Figures 8 to 11 in Weymouth Bay in January for a source at 5m depth and receiver at 10m depth at 11.3kHz. In this environment, groups of eigen-rays are received with similar power levels (Figure 8). Transmission loss is higher in winter because higher wind speeds result in greater scattering at the sea surface (Figure 9). The time spread between the dominant eigen-rays is low and is less than 3ms at ranges up to 10km (Figure 10). The low time spread is primarily due to the shallow water depth in this environment.

Relative motion between the transmitter and receiver introduces Doppler spreading of the signal in frequency due to differing rates of change of path length for each eigen-ray. Energy scattered from a moving sea surface also introduces Doppler spreading of the signal. Surface waves have a greater effect on Doppler spreading than platform motion in the Weymouth Bay environment due to the shallow water depth and low time spread of the received eigen-rays (Figure 11). Doppler spreading increases at short ranges and is less than 1Hz at ranges less than 1km.

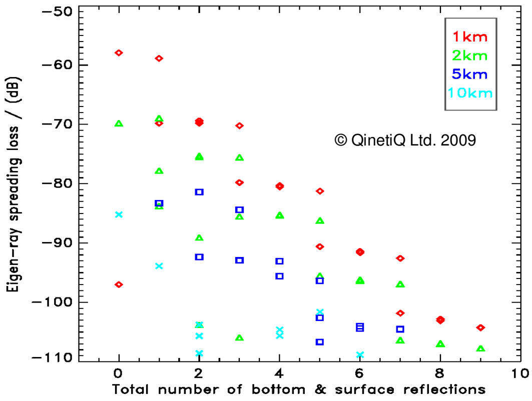

Figure 8: Eigen-ray spreading loss vs. total number of reflections in Weymouth Bay in January

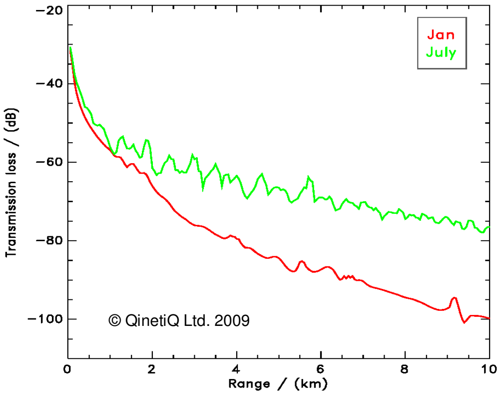

Figure 9: Transmission loss in Weymouth Bay for source at 5m depth and receiver at 10m depth, at 11.3kHz

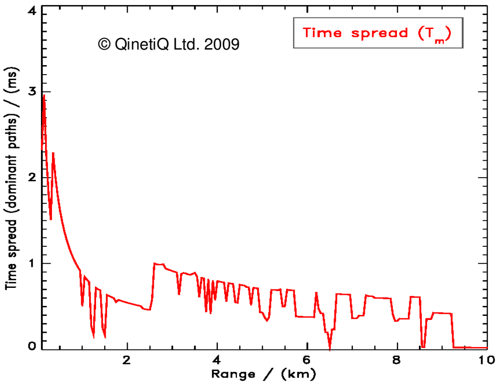

Figure 10: Time spread of dominant eigen-rays in Weymouth Bay in January

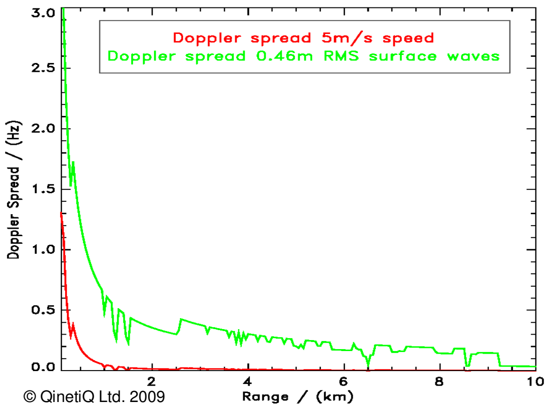

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Figure 11: Doppler spread of dominant eigen-rays in Weymouth Bay

Table 1 summarises the properties of the underwater sound channels in the three environments in January.

In winter, the North Atlantic environment provides an ideal underwater sound channel. The dominant arrival propagates via a direct line-of-sight path which does not interact with either the sea surface or seabed. Energy reflected from the sea surface is typically attenuated by at least 6dB. The time spread in the North Atlantic channel is low (less than 2ms) at short ranges since bottom reflected energy is heavily attenuated at high incidence angles.

Many more eigen-rays are present in shallow water environments such as Weymouth Bay and the Strait of Hormuz. For example, between 6 and 9 dominant eigen-rays are present in both shallow water environments at 2km range. A direct path arrival is not present in Weymouth Bay in July or in the Strait of Hormuz at 2km range. Consequently, the signal components received in these channels are scattered from the sea surface and seabed and are subject to fading.

Of the three environments considered, the Strait of Hormuz provides the most complex conditions. The Strait of Hormuz has the highest time spread (T_m) of 42ms in winter and 26ms in summer. Platform motion introduces significant Doppler spreading (B_d) of the signal (around 1Hz at 2km range) in the Strait of Hormuz environment due to the high time spread of the channel.

Table 1: Summary of channel characteristics at 11.3kHz

Environment	North Atlantic January	Weymouth January	Strait of Hormuz January
Sea state	5	4	2
RMS wave height	0.79m	0.46m	0.12m
Transmission loss	-60 dB	-65 dB	-56 dB
No of dominant eigen-rays	2	6	9
Total number of eigen-rays	7	23	17
Direct path?	Yes	Yes	No
Multipath time spread	0.58ms	0.54ms	42 ms
Doppler spread, due to 5m/s Rx motion	0.016Hz	0.015Hz	1.2 Hz
Doppler spread due to surface waves	1.1 Hz	0.35Hz	0.84Hz
Spread factor @ 5m/s	7.e-4	2.e-4	0.05

Doppler spreading due to surface waves is dependent on wave height and is greatest in the North Atlantic environment in winter (1.1Hz at 2km range).

The spread factor of the channel denotes whether it is possible to select a signalling scheme such that the channel is frequency non-selective and slowly fading. The spread factor is the product of the multipath time spread and the Doppler spread (T_mB_d) of the channel. The channel is considered to be under-spread when the spread factor is less than unity and this is observed to be the case in all three environments considered in the assessment at a range of 2km. Consequently, it is possible to select a signalling scheme such that the channel is frequency non-selective.

Note that the time spread is dependent on water depth and large time spreads may be present in deep water channels. For example, time spreads exceeding 1s are present in the North Atlantic Sea at ranges greater than 10km in both summer and winter.

Transmitted Waveforms

The transmissions are designed to test how the proposed multicarrier scheme would cope with several propagation conditions. For this purpose, the environments are chosen in which both, the time spread and the Doppler spread are present to various degrees.

The transmitted signal is organised into frequency blocks which carry QPSK modulation at various symbol rates and guard-bands. A common symbol rate and guard-band will be selected, which copes well with all scenarios. For this, the system will be configured so, that:

1/R>>TS and GB>DS

Where TS is the time-spread and DS is the double sided Doppler spread of the channel and GB is the guard-band, i.e. the bandwidth allocated for the pilots.

The frequency plan and channel parameters for a block are shown in Table 2.

Table 2: Transmit frequency plan

Carrier freq [Hz]	Rate [Hz]	Guard-band [Hz]
224	16	8
160	16	6
42	8	4
14	8	3
-14	8	3
-42	8	4
-143 -157 -227 -241	4	2
-143 -157 -227 -241	4	1.5

The blocks are repeated over the entire frequency band of 8 KHz to 16 KHz. The channels are RRC filtered at α=0.25. The spectrum of a frequency block is shown in Figure 12.

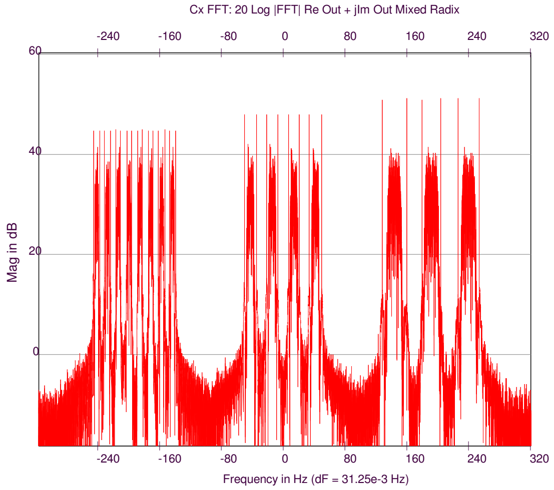

Figure 12: Transmit spectrum of a block

The transmitted time series consists of 1024 bits at a sample rate of 48 KHz. The source data is transmitted in two channels at 16 Hz rate. The same data is de-multiplexed and transmitted in four channels at 8 Hz rate and also in eight channels at 4 Hz rate. The total length of the transmissions is 32 seconds, and in a block a total of 6.2 Kb data is transmitted.

There are 12 identical blocks fitted into the 8 KHz bandwidth. These are shifted to the 8 KHz-16 KHz band and then the real part is applied to the ACS system.

Receiver Architecture

The receiver comprises a block down-converter followed by a plurality of demodulators operating autonomously on each sub-carrier. The challenge is to coherently demodulate a signal that is buried in the time-variant environment.

Because of the rapid variations, it is not possible to use techniques, such as a training sequence, commonly used in radio communications. However, a concurrent reference is necessary for the channel estimation. In this respect, this technique is similar to that of the TTIB technique [6] but without splitting the data into USB/LSB components.

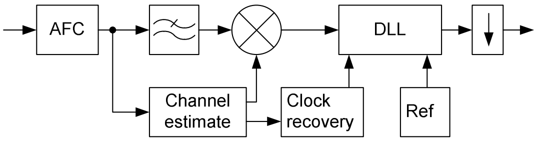

Figure 13: Demodulator block diagram

Figure 13 shows the top level block diagram for the demodulation. The down-converted signal is applied to an Automatic Frequency Control loop that tracks the long term frequency variations. The loop is locked to the adjacent pilots.

In the present frequency plan, due to the channel effects, a full channel bandwidth was necessary for the pilots to provide adequate guard band for filtering and for the AFC loop. This means that the maximum throughput is 1 bit/sec/Hz for QPSK. Even with this overhead, the AFC loop could not track the 4Hz channels in some circumstances. Furthermore, the AFC in its present form introduces additional noise, which deteriorates the system performance by around 0.5 dB at 8Hz symbol rate.

To solve the AFC problem, some pilots should have increased guard bands for pre-tuning. These pilots would control a coarse AFC to pre-tune the receivers for a block of frequencies prior to down-sampling.

The channel estimator acts on the adjacent pilots and tracks the instantaneous variations in both amplitude and phase. These impairments are then removed from the IQ data. The instantaneous phase is estimated by averaging the phases of the USB and the LSB pilots.

There is an initial phase ambiguity of π due to the phase averaging, this is removed during acquisition. In deep fades in some circumstances, the channel parameters change to an extent that re-acquisition may be required when the signal returns. Under these conditions a burst of errors occurs; this is reflected by the performance curves of Figures 14, 16 and 17. The minimisation of these errors is a critical part of the receiver design. The present algorithm would benefit from further optimisation in this area.

Timing signals are readily available from the envelope of the summed pilots as the pilots move synchronously with the symbols. The time-variant symbols are synchronised to the reference data using a Delay Locked Loop for the subsequent decimation.

Simulation Results

The Bit Error Rate (BER) curves versus Eb/No ratios are shown in Figures 14, 16 and 17 for Weymouth Bay, for the North Atlantic and for the Strait of Hormuz in winter environments. These locations were chosen to represent benign, typical and complex propagation conditions. A symbol rate of 8 Hz was chosen for all scenarios as this represented the best compromise with the present architecture.

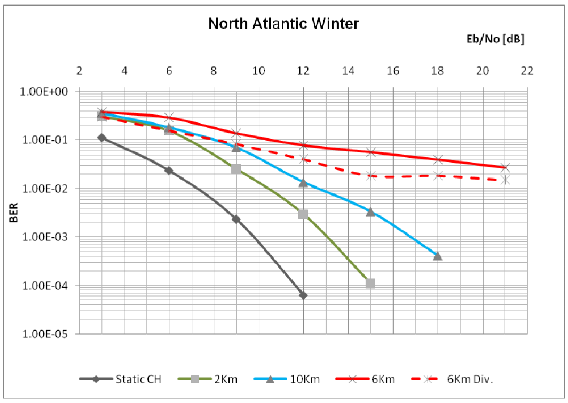

Figure 14: Performance in North Atlantic Winter environment

It is interesting to note, that in the North Atlantic Winter environment the worst performance is experienced at a range of 6 km and then the BER becomes better at 10 km.

Figure 15 shows that in fact the fades are deeper for the 6 km range than that for the

10 km range for this particular section of the time series. This kind of effect could be minimised by processing a longer time series in the future.

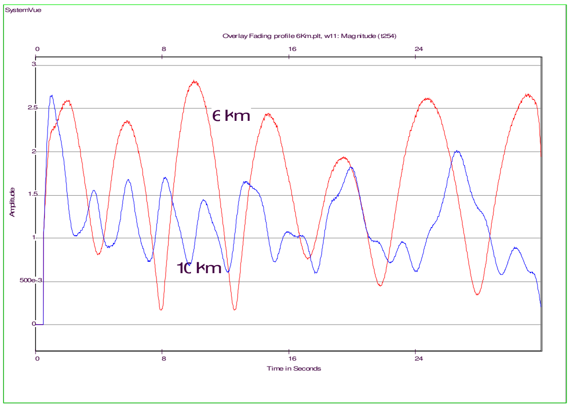

Figure 15: Fading profiles for North Atlantic Winter 10 km and 6 km range

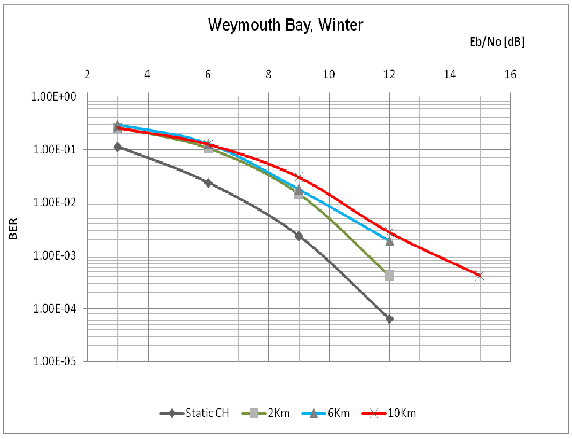

Figure 16: Performance at Weymouth Bay, winter

Weymouth Bay represents a typical environment. The BER performance is very similar to that of North Atlantic Winter location. This is shown in Figure 16.

The most difficult environment is represented by the Strait of Hormuz. Here severe multipath propagation takes place coupled with high Doppler spread. The spread factor at a velocity of 5 m/s ranges between 0.02-0.05 (see Table 1). Clearly, under these conditions, it is very difficult to establish acoustic communication.

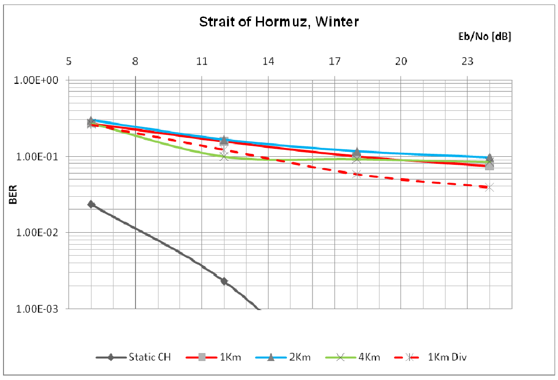

Figure 17: Performance at Strait of Hormuz, winter

In the present architecture, the demodulator lost synchronisation several times, leading to very high error rates. It is anticipated that by improving the phase estimation method, better performance could be achieved.

Finally, the performance for two channel frequency diversity was simulated. The frequency separation is 1.5 KHz; this completely de-correlates the channels. Typically 2-6 dB improvement was achieved as shown on Figures 14 and 17 (dotted line). Maximum Ratio combiner was used in these simulations.

Conclusions

The performance of a multi carrier modulation scheme was verified using a time domain acoustic simulator. Three different environments were chosen to represent realistic propagation conditions. The speed was set at 5 m/s and the distance was varied between 2 Km to 10 Km. 1b/sec/Hz throughput was achieved.

Within a short time span of 32 seconds, in both the benign and in the typical environments the BER was between 10^{-2} and 10^{-3} most of the time, with Eb/No values of 10-15 dB respectively.

It was shown that the concept of splitting up the frequency band into narrow band carriers provides a good solution for the challenging conditions of the shallow water environment. However, in a complex environment the synchronisation requires particular attention and therefore further work is needed this area.

It is proposed that a two-stage AFC should be implemented both to enhance the frequency tracking of the receiver and to facilitate operation down to 4Hz symbol rate. This in turn would further improve the ability of the system to cope with Doppler and multipath in a complex environment.

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Acknowledgements

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