On the Variability of Optimal Transmission Frequency for Underwater Acoustic Communication in the North-Western part of the Black Sea

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***Abstract*—The underwater acoustic communication channel (UACC) is considered the most challenging one because of the long and variable multipath, limited bandwidth and Doppler shifts. The variability of the underwater acoustic channel is caused by daily or seasonal changes of the marine environment, and must be carefully considered in design of underwater communication equipment, such as underwater acoustic modems (UAM). Therefore it is necessary to accurately determine the changes of the acoustic parameters of the marine environment when an UAM is being designed.**

In addition, some local physical characteristics of the underwater environment have to be taken into account. In this article we present the environmental model of the underwater acoustic communication channel which is located in the north-western part of the Black Sea and is based on mean seasonal changes of the sound speed profile and mean geophysical properties of the seafloor. The proposed environmental model is simulated and the results are used to describe the variability of an acoustic model. The acoustic channel is characterized in terms of attenuation and optimal transmission frequency for each season, depending on the transmission distance.

***Keywords*- acoustic model, environmental model, optimal transmission frequency, underwater acoustic communication channel, underwater acoustic modem.**

I. INTRODUCTION

Using marine research platforms and numerous sophisticated devices, scientists gathered information about sediment composition and stratification, water depth, temperature, salinity and wind speed. Based on these data they proposed general formulas for the surface and bottom attenuation, transmission loss and noise level that were used to characterize the mean oceanic communication channel. These equations are often used to design underwater communication systems [1].

It is known that daily variations of the acoustic parameters of the marine environment could cause fast fluctuations in the acoustic channel and seasonal variations could cause the change of shape of the amplitude-delay profile [2], [3]. If these variations are well known, then the underwater acoustic communication channel could be characterized in terms of the optimal transmission frequency which is the frequency that is the least affected by the cumulative effect of the transmission losses and noise level.

Information about the optimal transmission frequency can be used to design an underwater acoustic modem [4]. Created in this way, the UAM is adapted to a particular UACC and it will operate efficiently in the marine environment because it knows the channel variations.

In [5] and [6] the authors describe the architecture of an underwater acoustic modem equipped with an equalizer to cope with the variations of the underwater acoustic channel. Using the equalizer, the modem efficiently processes the received signals, but it uses a lot of power and can not be used for long term monitoring activities. In [7] the authors begin the design of an UAM from the properties of a home-made underwater transducer and the properties of the mean oceanic communication channel. The cost of the modem is low because of the home-made transducer but has a fixed architecture. The author of [8] presents an adapted underwater transmitter which was designed using information about the daily and seasonal variations of the optimal transmission frequency for the underwater acoustic channel at the mouth of the Danube Delta.

In this article we present an environmental and acoustic model for an UACC located in the north-western part of the Black Sea. The results were obtained by simulating the underwater sound propagation in the proposed channel. We compared our results with the mean oceanic communication channel which is emphasized in [9] and [10]. Afterwards, the simulation results will be used to design and implement an underwater acoustic modem.

The particular underwater acoustic communication channel was simulated with AcTUP, Acoustic Toolbox User interface and Post processor, whose operation is highlighted in [11] and [12]. This software runs under Matlab and is a graphical user interface written by Amos Maggi and Alec Duncan, which facilitates the rapid application of different acoustic propagation codes from Acoustic Toolbox, which were written by Mike Porter [13] – [15].

We must emphasize that this method of characterization allows the incorporation of real underwater acoustic data and a rapid configuration of the environmental and transmission parameters. It is worth mentioning that this is a cheap method for characterizing a particular underwater acoustic channel. There is also the experimental method but this is quite expensive because it requires many underwater transducers and hydrophones, sophisticated transmission devices, trained personnel and at least a research vessel. In most cases the simulation method is used first because it helps planning future experiments in the marine environment and allows an early estimation of the resources that will be used.

II. Underwater Acoustic Communication Channel Modeling and Simulation

The region of interest is shown in Fig. 1. It was named Constanța after the most important city port in the Black Sea region belonging to Romania. It is geographically located between 28.5 E and 30.5 E longitudes and between 43.5 N and 44.8 N latitudes. This zone has a length of 222 km, a width of 127 km and an area of 28194 km. In this region were recorded 3432 sound speed profiles, therefore we have a resolution of one measurement on an area of 8 km2.

The average depth is 75 m. Based on this datum our underwater acoustic communication channel is shallow. Its depth is smaller than 200 m, the maximum depth of a shallow water channel.

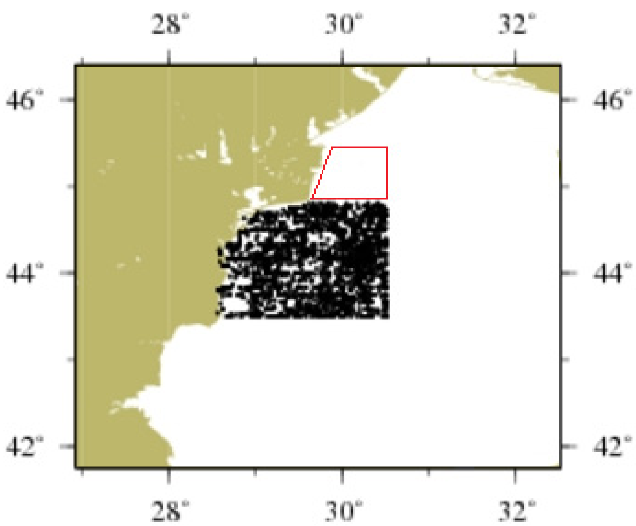

Figure 1. Constanța region and the distribution of the recorded data.

A. The environmetal model

The environmental model of the considered underwater acoustic channel was created using conductivity, temperature, depth (CTD), and wind speed data obtained from the National Oceanic and Atmospheric Administration (NOAA) [16].

The CTD data and (1) [17] were used to compute the sound speed profile for the Constanța region. The coefficients of the above equation are presented in Table 1.

$$c = a_1 + a_2 T + a_3 T^2 + a_4 T^4 + (a_5 + a_6 T)(S + a_7) + a_8 z \quad (1)$$

In (1) c is the speed of sound in m/s, T is the temperature in degrees Celsius, S is salinity in parts per thousand (ppt or ‰) and z is the depth measured in meters. This equation is valid for $0^o \leqslant T \leqslant 35^o$ C, $0 \leqslant S \leqslant 45$ ‰ and $0 \leqslant z \leqslant 1000$ m.

We organized the computed sound speed profiles in four categories, one for each season. Afterwards we averaged the SSPs for each season and we obtained four mean sound speed profiles. These are shown in Fig. 2.

TABLE I. SOUND SPEED COEFFICIENTS

Coefficients	
a1	1449.2
a2	4.6
a3	-55•10-3
a4	290•10-6
a5	1.34
a6	-10•10-3
a7	-35
a8	16•10-3

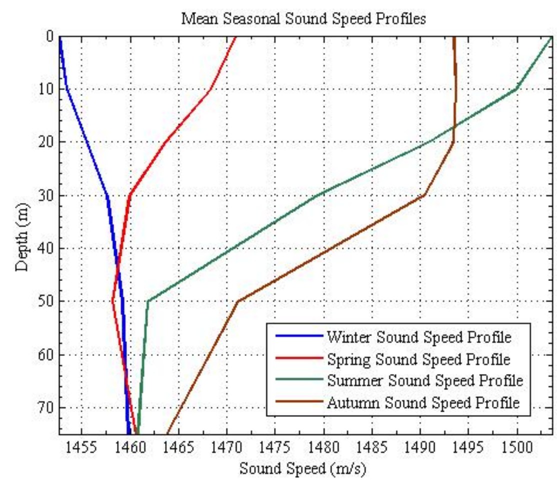

Figure 2. Mean seasonal sound speed profiles for the Constanța region.

In Fig. 2 we observe that most of the values are smaller than 1500 m/s, the average sound speed in water. This is mainly due to the low salinity in this area which is located near the Danube Delta region. This region is represented by the red polygon in Fig. 1. The Danube Delta is the main source of fresh water for the Constanța region.

As we advance from winter season to summer season we notice in Fig. 2 an increase in the speed of sound, for depths between 0 and 44 m, determined by a gradual increase of the temperature. The transition from summer season to fall season causes a decrease of the temperature, hence a decrease in the speed of sound, for depths between 0 and 18 m.

During winter we observe that the sound speed increases with depth, phenomenon known as the mixed layer, which is due to the harsh weather conditions that determine a constant temperature in the water column.

As we transition from winter to spring we see that the geometry of the profile has changed because the weather conditions have improved. We notice a decrease in the sound speed with depth which is known as the thermocline. Between 50 and 75 m the mixed layer is present.

In the summer season the good weather that lasts the entire day determines an increased gradient between the surface and the seafloor temperatures which causes a pronounced thermocline.

In autumn we observe an isovelocity layer between 0 and 20 m which continues with a thermocline layer consisting of three regions with different slopes.

The seabed is the lower boundary of the communication channel and can reflect and scatter the transmitted underwater signals. We must emphasize that a careful modeling of the seabed will determine good results in channel simulation.

In Table 2 we present the sediment composition of the seafloor and the geophysical properties [18]-[20]. This seabed has a very complicated structure consisting of six layers with different thicknesses, sound speeds and densities. Fig. 3 shows the sound speed profile of the seafloor [18]-[20]. We specify that the sixth sedimentary layer is deeper than 1 m.

TABLE II. GEOPHYSICAL PROPERTIES OF THE SEAFLOOR SEDIMENTS

Geophysical properties				
Layer Name	***Depth (m)***	***Sound speed (m/s)***	***Density (kg/m³)***	***Attenuation coefficient (dB/ λ)***
Silty-Clay	0.0375	1517	1480	0.15
Sandy-Clay	0.0375	1555	1490	0.2
Clayey-Sand	0.075	1596	1493	0.2
Sand-Silt-Clay	0.15	1582	1575	0.2
Silty-Sand	0.02	1658	1783	0.2
Sand	>1	1650	1900	0.2

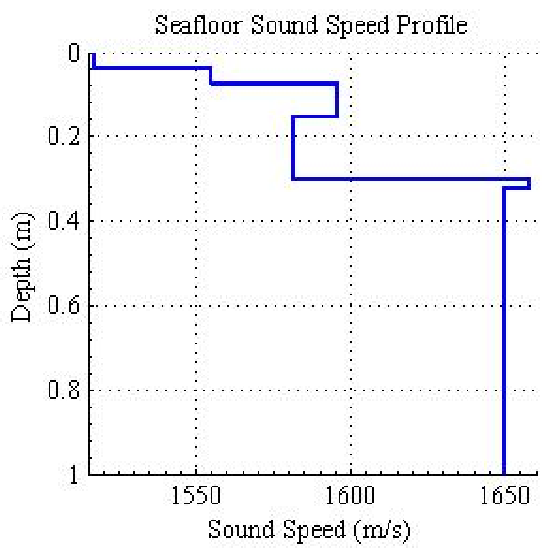

Figure 3. Seafloor sound speed profile.

The sea surface is the upper boundary of the sound channel and is considered to be both a reflector and a scatterer for the transmitted underwater signals.

There is a strong relationship between the sea surface roughness and the wind speed at the surface. The height of the waves can be estimated with the statistical relationship described by (2) [21].

$$h_{rms} = 1.505(10w)^{-2} \quad (2)$$

In (2) hrms is the wave height measured in m and w is the wind speed measured in m/s.

We chose the wind speed equal to 10 m/s which means that at sea there are waves with moderate heights. The Beaufort number for this wind speed is 5 and the wind description is fresh breeze. Using (2) we obtain a root mean square wave height of 1.505 m.

We introduced the sound speed profiles, the seabed sediment configuration and the wind speed in AcTUP simulation software. We created four underwater environments, one for each sound speed profile. In Fig. 4 we show the environmental model of the underwater acoustic communication channel for the considered region. The transmitter and the receiver are placed at 1 m above the seafloor and are considered fixed. This transmission configuration will eliminate the Doppler shift introduced by the motion of the acoustic communication devices. We also considered three transmission distances 500, 1000 and 2000 meters.

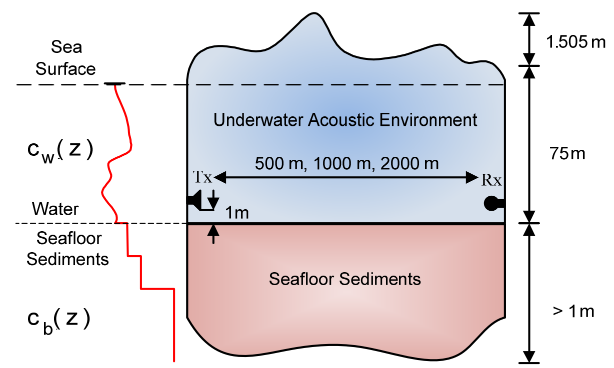

Figure 4. Environmental model of the UACC in the north-western part of the Black Sea. The sea depth, z, is measured in meters, $c_w(z)$ represents the water SSP and $c_b(z)$ the seafloor SSP.

B. The simulation method

In this subsection we present the method that we used to simulate the environmental model presented in Fig. 4. The results were obtained using AcTUP and the acoustic propagation algorithms named Bounce and Bellhop, which are ray tracing programs.

The Bounce algorithm is run first, using the geophysical properties of the seafloor sediments. It creates a file in which we can find the bottom reflection coefficient as a function of the grazing angle. Afterwards the Bellhop algorithm is run, using the bottom reflection coefficient, the sound speed profile, the wind speed, and the transmission configuration. It computes the propagation of the transmitted energy through the underwater acoustic channel taking into account the interaction with the seabed and the sea surface. Specifically the algorithm traces rays of energy that can reflect or refract in the underwater environment. Thus we obtained a ray tracing diagram and an example is shown in Fig. 5. Afterwards only the rays that connect the transmitter and the receiver are selected, which are known as eigenrays and all the other rays are deleted. An eigenray diagram is shown in Fig. 6. Obviously, the rays arrive at the receiver with different delays and magnitudes. Their delays are computed using the eikonal equation [19] and the sound speed profile and their magnitudes are computed using the transport equation [19] and the attenuation coefficients, according to Thorpe's formula [3], knowing the distance traveled by each eigenray and the number of interactions with the seabed. The attenuation coefficient is represented as a function of frequency in Fig. 7. Therefore the amplitude of each eigenray will be influenced by the transmission frequency.

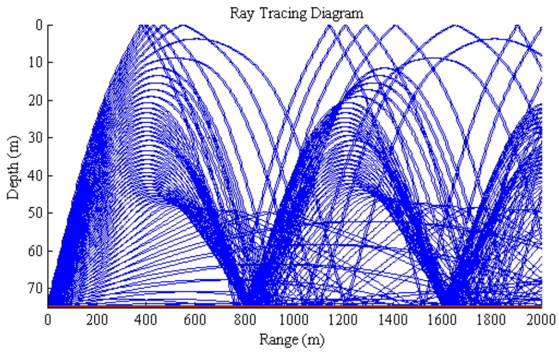

Figure 5. Ray tracing diagram for a transmission distance of 2000 m. Tx and Rx are placed at 1 m above seabed.

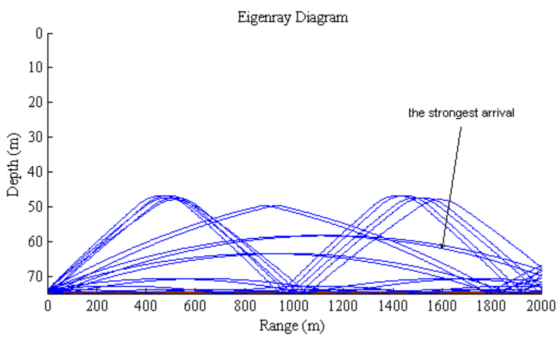

Figure 6. Eigenray diagram for a transmission distance of 2000 m. Tx and Rx are placed at 1 m above seabed.

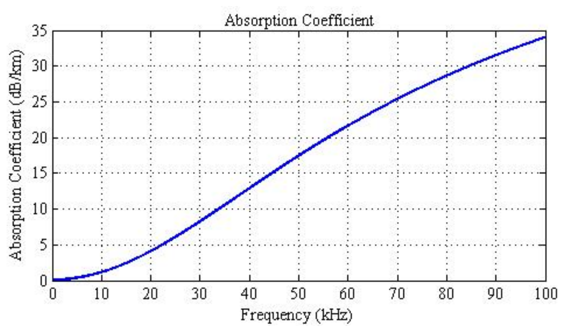

Figure 7. Absorption coefficient measured in dB/km.

The method described above is applied by AcTUP for a specific transmission configuration and for each frequency in a particular bandwidth and then it runs Bellhop, which creates an amplitude-delay profile for each frequency.

In Fig. 8 we show three amplitude-delay profiles that were obtained in the summer season, for frequencies 1, 10, and 90 kHz, for a transmission distance equal to 2000 m. In this figure we observe that the amplitude of the delayed impulses decreases when the transmission frequency increases. Also the strongest arrival is not represented by the first impulse. This is because the first arrival travels the fastest and interacts with the sedimentary layer, which strongly attenuates its amplitude. The strongest arrival is represented in Fig. 6 and it does not interact with the bottom.

We processed these amplitude-delay profiles and obtained a frequency-dependent frequency response for the considered UACC.

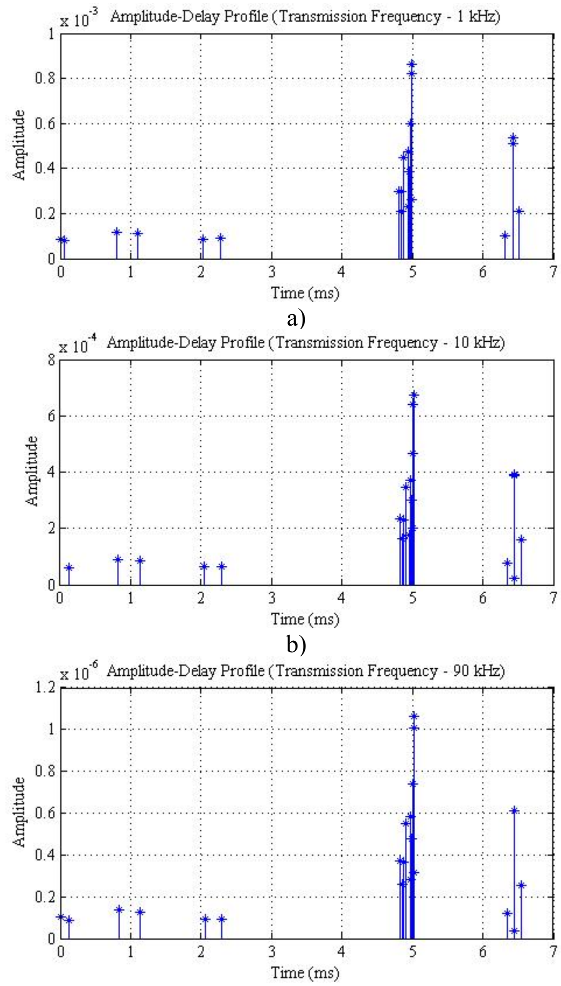

Figure 8. Three amplitude-delay profiles of the considered underwater acoustic communication channel.

C. The acoustic model

We simulated the proposed underwater acoustic channel in the frequency range 0.1-99.9 kHz with a resolution of 0.1 kHz, for each season and for the transmission distances given in subsection A. We obtained 11988 amplitude-delay profiles and we used these and (3) to compute the frequency response of the channel. This equation is a simplified version of the equation presented in [9].

In (3) f is the transmission frequency, l is the transmission distance, τ is the relative delay, A is the amplitude, H is the frequency response and i represents the i^{th} arrival or the i^{th} delayed impulse.

$$H(f,l) = \sum_i A_i(f,l)e^{-j2\pi f\tau_i} \quad (3)$$

We used (4) and the frequency response results to compute the transmission losses in the channel. These results are presented in Fig. 9 for each season and for each transmission distance as a function of frequency.

$$TL(f,l) = -10\log_{10}\left(\left|H(f,l)\right|^2\right) \quad (4)$$

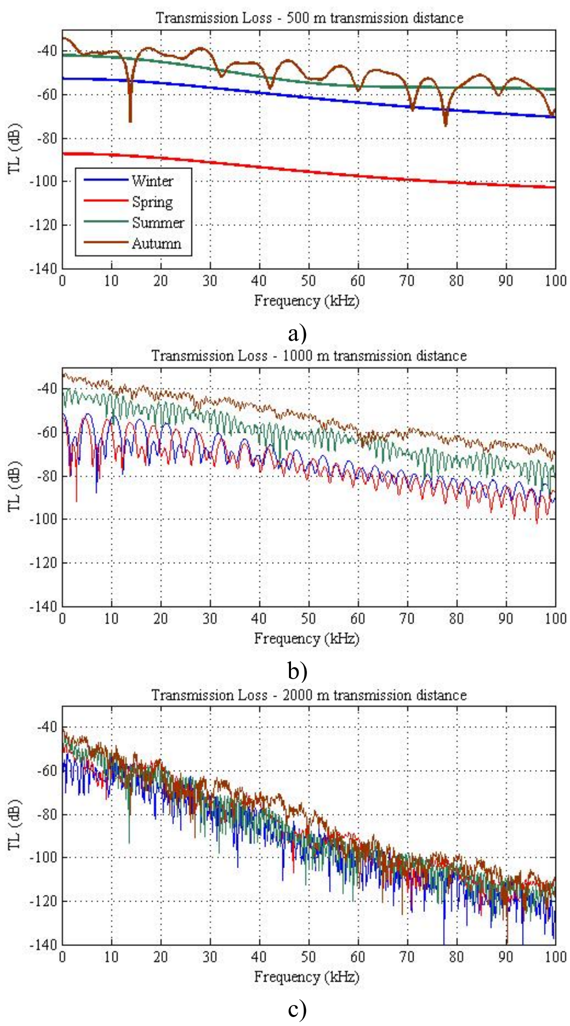

Figure 9. The parameter TL represented as a function of frequency, for each season and for three transmission distances.

In (4) TL is the transmission loss that characterizes the acoustic model of the underwater channel and is measured in dB. We observe smaller transmission losses in the summer and autumn than in the winter or spring. Therefore a small bit error rate is expected winter or spring. We notice in Fig. 9.a that the losses in the spring are greater, on average by 50 dB, than those in other seasons. This is due to the fact that the spring sound speed profile creates a shadow zone around 500 m from the transmitter. Also in this figure we see a moderate selectivity in the autumn. This is more pronounced as the transmission distance increases. The selectivity is due to the destructive combination of the delayed impulses at certain frequencies at the receiver. The difference between the seasonal TL profiles tends to minimize as the transmission distance increases.

It can be rapidly observed that losses increase with the transmission frequency and the mean rate of decay for 0.5 km is 0.6 dB/kHz, for 1 km is 0.65 dB/kHz and for 2 km is 0.7 dB/kHz.

Equation (5) highlights the second acoustic parameter named noise level, NL, and is valid for the frequency range 0.1-99.9 kHz. We emphasize that the ambient noise depends on the wind speed w and we chose w equal to 10 m/s.

$$NL = 50 + 7.5w^{0.5} + 40\log_{10}\left(\frac{f^{0.5}}{f+0.4}\right) \quad (5)$$

The cumulate effect of the transmission loss and noise level parameters is named the total attenuation, TA.

$$TA = TL + NL \quad (6)$$

III. Optimal Transmission Frequency

From the TA we find the optimal transmission frequency using (7). This frequency is obtained when the cumulated effect of the acoustic parameters is at a minimum.

$$f_{opt}(l) = \arg\max_f TFR(f,l) \quad (7)$$

The total attenuation is an integral part of the passive sonar equation

$$SNR = SL - TA \quad (8)$$

where SNR is the signal-to-noise ratio at the receiver and SL, (source level), is the power that could be generated by the transmitter.

If we want to accurately determine the SNR at the receiver for a particular frequency, we need to measure or estimate the variability of the underwater acoustic channel. Told otherwise when an electrical engineer designs an underwater communication device he must know the channel variability to determine the optimal transmission frequency, afterwards to choose a suitable projector to provide the best signal-to-noise ratio at the receiver.

In Fig. 10 we highlight the variability of the proposed underwater acoustic communication channel through the optimal transmission frequency. We compared the optimal frequencies obtained for each season with those for the mean oceanic communication channel, MOCC [22].

We observe that the optimal frequencies for the considered distances, for winter and spring seasons are approximately equal to the optimal frequencies of the MOCC. However we notice a large deviation from the mean of the optimal frequency at 0.5 km in the summer season. We also see a moderate deviation for 0.5 and 1 km transmission distances in the autumn season.

We end this section emphasizing that the results presented in Fig. 9 could be used to create an adaptive transceiver for an underwater acoustic modem. Designed in this way the modem will be aware of the mean variations of the particular channel and will consume less power when transmits the acquired signals because it is adapted to the underwater acoustic communication channel.

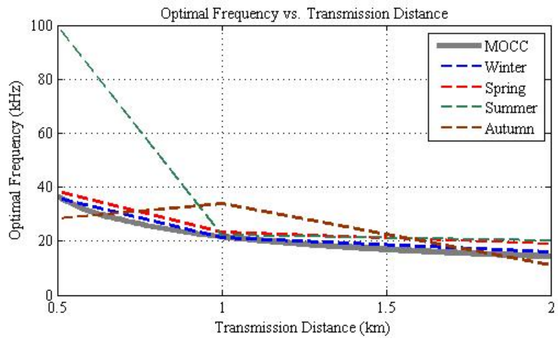

Figure 10. Optimal transmission frequency as a function of transmission distance. MOCC represents the optimal frequency of the mean oceanic communication channel.

IV. CONCLUSION

In this article we present an environmental and an acoustic model for the underwater communication channel located in the north-western part of the Black Sea. In order for the simulations to be accurate and comparable to the measurements results in the marine environment we used in this study mean seasonal sound speed profiles, bathymetric data, geophysical properties of the seafloor sediments and wind speed at the surface. Using AcTUP and the ray tracing algorithms Bounce and Bellhop we obtained the attenuation in the channel in the frequency band 0.1-99.9 kHz, for each season and for three medium transmission distances. We also computed the average loss as a function of frequency, which naturally increases with the transmission distance, but not under a linear law.

We considered the cumulative effect of the transmission losses and the ambient noise level and we computed the optimal transmission frequency for each season and for the three transmission distances. We compared the simulated results with the mean oceanic communication channel and we noticed that the optimal transmission frequency for the winter and spring seasons are approximately equal to those of the MOOC. In the summer season at 0.5 km and in the autumn season at 1 km we observed that the optimal transmission frequency is greater than that of the MOOC, meaning that the transmission communication speed could increase, that is a bigger bandwidth is available. On the other hand in the autumn season at 0.5 km and 2 km the optimal transmission frequency is smaller than that of the MOCC, which means that the transmission speed will decrease accordingly.

These results will be used to design and implement an underwater acoustic modem for long term monitoring applications in the considered region.

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