Defence Research and Development Canada
Recherche et développement pour la défense Canada

CAN UNCLASSIFIED

DRDC | RDDC
technologysciencetechnologie

Simultaneous Design of Underwater Acoustic Sensor and Communication Networks

Stéphane Blouin
DRDC – Atlantic Research Centre

Proceedings of the International Conference on Underwater Networks & Systems
Halifax, NS, Canada—November 06–08, 2017
Article No. 16, 5 pages

Date of Publication from Ext Publisher: November 2017

Defence Research and Development Canada

External Literature (P)
DRDC-RDDC-2018-P075
May 2018

CAN UNCLASSIFIED

Canada

IMPORTANT INFORMATIVE STATEMENTS

Simultaneous Design of Underwater Acoustic Sensor and Communication Networks

Stéphane Blouin*
stephane.blouin@drdc-rddc.gc.ca
Defence R&D Canada - Atlantic Research Centre
Underwater Sensing & Communication (USC)
Dartmouth, NS, Canada

ABSTRACT

Many papers discuss challenges and solutions pertaining to underwater networks that make use of acoustic waves for either detection or communication purposes. However, no known solution yet exists for jointly conceiving network performing both tasks. This publication proposes a procedure addressing this shortcoming. While considering environmental conditions and physical design decisions, the approach leads to a closed-form expression that has an optimal communication source level solution. Moreover, results compare favorably with experimental data.

KEYWORDS

Underwater networks, acoustic detection and communication, simultaneous design

ACM Reference Format:
Stéphane Blouin. 2017. Simultaneous Design of Underwater Acoustic Sensor and Communication Networks. In *WUWNET'17: WUWNET'17: International Conference on Underwater Networks & Systems, November 06-08, 2017, Halifax, NS, Canada.* ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3148675.3148676

1 INTRODUCTION

Underwater acoustic networks have been a topic of interest for more than two decades [4] with applications in the military, private, and security domains [10]. The main benefit of using acoustic waves under water relates to their propagation ranges far exceeding those resulting from electromagnetic or optical waves. In a network using acoustic waves for both detection and communication, each network node operates an acoustic modem and utilizes underwater microphone (hydrophones) to acoustically detect objects of interest.

Surveys [5, 7, 12] reviewed the progress made on acoustic communications and remaining challenges. Similarly, Traweek and Wettergreen [15] investigated the sensing design question, but without considering acoustic communications as an integral part of the problem. Moreover, in [7] authors highlight the necessity for new theoretical models and for the inclusion of aspects pertaining to the physical design and cost of those networks. Such a physical design analysis would entail the selection of the required number of hydrophones, their spacing, as well as the spatial placement of network nodes, among other things.

The typical design of a SONAR system, either for detection or communication, naturally results in an optimization problem with various constraints pertaining to cavitation, processing gain, dimensions, etc. The physical design of an underwater network where each node acoustically detects and communicates is even more challenging because the detection and communication tasks may occur in different frequency bands, thus imposing two significantly distinct sets of constraints.

A new procedure for performing the simultaneous design of the sensing and communication functions of each underwater node is proposed. In particular, the proposed technique provides guidance in terms of node separation distance and communication frequency-band while considering physical design decisions and environmental conditions. To the author's knowledge, this is the first time such a simultaneous sensing-and-communication design procedure is presented. Moreover, the results favorably compare with acoustic communication experimental data.

Section 2 defines in more detail the problem at hand. In Section 3, the proposed approach and solution are explained. A case study and its outcome are used to convey the technique in Section 4, before concluding with Section 5.

2 PROBLEM DEFINITION

The main challenge being investigated here is the design of an underwater sensor network capable of: (i) detecting an acoustic signature (called 'target') far outside the network, and (ii) communicating between nodes within the network.

There are four main components to this problem space, whose first three components are: the target (identified with subscript 'T'), the sensing (subscript 'S'), and the communication (subscript 'C'). The fourth component is associated to environmental features, like wind, sound speed profile, etc., that are partially known (or inferred) and expected to slowly vary over time. The main two target features considered here are the main tonal frequency, f_T, and its source level, SL_T.

3 PROPOSED SOLUTION

3.1 Assumptions

These common assumptions hold:

*The corresponding author

WUWNET'17, November 06-08, 2017, Halifax, NS, Canada

ACM ISBN 978-1-4503-5561-2/17/11…$15.00
https://doi.org/10.1145/3148675.3148676

(*I*) The target radiated noise is narrow band, or *tonals*;
(*II*) Sensed and communicated acoustic signals are in the far field and coherent;
(*III*) Noise is isotropic, Gaussian, and white;
(*IV*) The effects of rain and ice are omitted;

along with the additional main assumptions:

(*V*) For acoustic communications, the same transducer serves both transmit and receive roles, as in most commercial modems;
(*VI*) Probabilities of detection and false alarms are 50%;
(*VII*) The target radiates omni-directionally, that is, the target directivity index is $DI_T = 0$;
(*VIII*) The ambient noise resulting from wind speed w (m/s) and shipping equally affect sensing and communication.
(*IX*) The target-to-node sensing range, R_S (in km), and the node-to-node communication range, R_C (in km), relate as follows

$$R_S = \beta R_C \tag{1}$$

where $\beta > 0$ is a real scalar.

Assumptions (*V*) to (*IX*) are only there to streamline the solution in the alloted space. Guidance for more general assumptions is given, thus demonstrating how general the proposed solution is.

3.2 Overall approach

Next, two SONAR equations, one for acoustic communications and one for target sensing, are re-introduced. For both communities (acoustic comms. and underwater sensing designer), most terms in their respective SONAR equation relates to path losses and transmitter/receiver effects, including antenna design. The main result of this section pertains to the formulation of a single expression capturing the challenges of designing hardware for performing both acoustic communication and target sensing.

For target sensing, signal excess (symbol SE) is given by the passive SONAR equation written as [2]

$$SE_S = SL_T - PL_S - NL_S - DT_S + DI_T + DI_S, \tag{2}$$

where all terms in decibels (dB relative to 1 μ-Pascal at a distance of 1 metre) and meaning: source level (SL), propagation loss (PL), noise level (NL), detection threshold (DT), and directivity index (DI). The frequency bandwidth term, BW, separately stipulated in some texts (like [17]), is incorporated in DT here.

For acoustic communications, a similar approach is taken and assuming that the same transducer technology applies to both transmission (Tx) and reception (Rx), as stipulated in Assumption (V), thus resulting in equal directivities, the equation becomes

$$SE_C = SL_C - PL_C - NL_C - DT_C + 2DI_C. \tag{3}$$

If Assumption (V) does no hold, then two terms $DI_{C,Tx}$ and $DI_{C,Rx}$ should replace $2DI_C$ in equation (3). From a performance standpoint, signal excess must minimally be equal to zero. Therefore, the least restrictive case $SE_S = SE_C = 0$ is chosen. This leads to the difference equation $SE_S - SE_C = 0$ and

$$\Delta SL = SL_T - SL_C = \Delta PL + \Delta NL + \Delta DT - \Delta DI, \tag{4}$$

where $\Delta PL = PL_S - PL_C$, $\Delta NL = NL_S - NL_C$, $\Delta DT = DT_S - DT_C$, and $\Delta DI = -DI_T - DI_S + 2DI_C$.

3.3 Detailed solution

Now that the problem has been posed as single equation, the following text will elaborate on the simplification of each right-hand side term of equation (4).

3.3.1 Propagation losses ΔPL. The propagation loss can be expressed as losses due to geometrical spreading and attenuation

$$PL(f, R, \gamma, K) = K \log_{10}(R \cdot 1000) + \alpha(\gamma, f) R, \tag{5}$$

where f, R, γ, K, and α are the frequency (in kHz), the range (in km), the environmental data (defined later), the spreading coefficient (taking value 10, 15, or 20 based on the implied spreading loss), and the attenuation coefficient (in dB/km), respectively. Now, using the expression $K = 10\,K^*$ with $K^* \in \{1, 1.5, 2\}$ and injecting equation (5) and assumption (*IX*) in the first right-hand term of equation (4) ultimately simplifies to

$$\Delta PL = 10 \log_{10}\left(\beta^{K_S^*}(1000\,R_C)^{K_S^*-K_C^*}\right) + \ldots \\ R_C(\alpha(\gamma, f_T)\,\beta - \alpha(\gamma, f_C)), \tag{6}$$

where f_T and f_C are the target tonal and acoustic communication frequencies, respectively. From [3], the attenuation coefficient $\alpha(\gamma, f_T)$ equals

$$B_1\left(\frac{f_T^2}{f_B^2 + f_T^2}\right) + B_2\left(\frac{f_T^2}{f_{Mg}^2 + f_T^2}\right) + B_3\, f_T^2, \tag{7}$$

where $\gamma = (pH, T, S, d)$, the environmental variable array, is made of the pH, the temperature (T) in Celsius, the salinity (S) in ppt, and depth (d) in km. The definition and range of coefficients B_i, f_{Mg}, f_B of equation (7) can be found in [3]. Simulating the entire range of environmental values, mean (subscript m) and upper bound (subscript u) values for attenuation can be approximated by frequency-only-dependent lines (in the log-log scale) thus giving

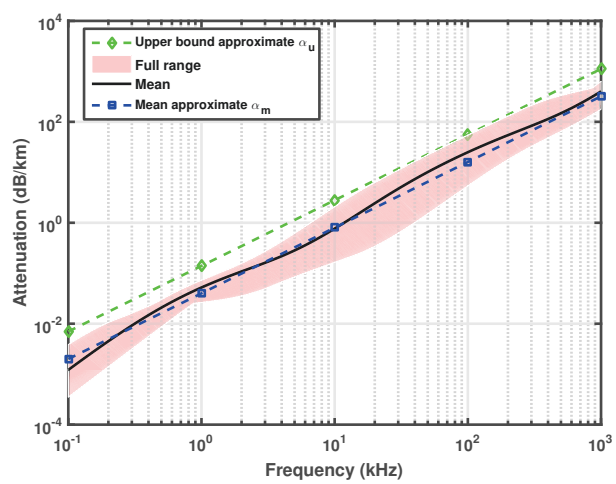

Figure 1: Attenuation range and mean values.

$$\alpha_m(f_T) = A_m\, 20^{(\log_{10} f_T)+1}, \alpha_u(f_T) = A_u\, 20^{(\log_{10} f_T)+1}, \tag{8}$$

where $A_m = 0.002$ and $A_u = 0.007$ so that attenuation grows by a factor of 20 dB/km for each decade of increase in frequency (ref.

α_m and α_u in Figure 1). Expanding equation (6) gives

$$\Delta PL = 10\ \log_{10}\left(\beta^{K_S^*}(1000\,R_C)^{K_S^*-K_C^*}\right) + \ldots$$
$$R_C\,\alpha_m(f_C)\left[\left(\frac{f_T'}{f_C}\right)^2 - 1\right], \tag{9}$$

where $\alpha_m(f_C)$ comes from equation (8) and $f_T' = \left(\frac{\beta\alpha_m(f_T)}{0.04}\right)^{0.77}$.

3.3.2 Ambient noise ΔNL. Many publications have discussed underwater ambient noise power spectra [1, 16, 18, 19]. The main ambient noise components, along with their preferential frequency bands, are: turbulence (< 10 Hz), shipping activities (10-to-200 Hz), surface agitation/waves (100-100,000 Hz), and thermal noise (> 100,000 Hz). For simplicity, rain and ice have been omitted.

In [13], the author proposes equations modeling each component. Similarly, Weinberg [18] documents equations matching the Wenz's curves. Figure 2 provides the whole ambient noise envelope generated from equations found in [13, 18] by considering the entire shipping traffic intensities (none to heavy) and wind speed (none to the maximum value on Beaufort scale). Figure 2 approximates the outer envelope of a more recent version of Wenz's curves (the blue lines) published in [1] and also shows the extreme cases of a wind-dependent approximation (in 1 Hz bands) proposed here

$$NL\ (\text{dB}) = 36 - 16\log_{10} f + 30\log_{10}(w-1), \tag{10}$$

with frequency f (kHz) and wind speed w (m/s). The proposed model falls between all three models discussed above for the maximum wind speed and is closer to the former Wenz and Coates models in the absence of wind.

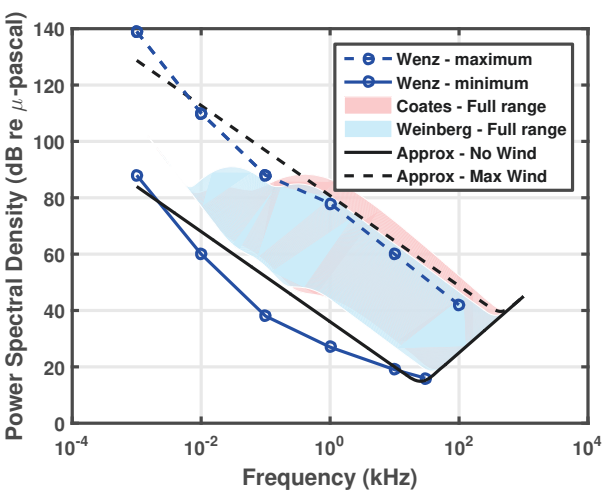

Figure 2: Ambient noise models [1, 13, 18] and proposed approximation.

Using the approximate model of equation (10), the resulting value ΔNL simplifies to

$$\Delta NL = NL_S - NL_C = -16\log_{10}(f_T/f_C), \tag{11}$$

when assuming that the same wind speed w holds over the area covered by sensing and communication ranges (ref. Assumption (*VIII*)).

3.3.3 Detection threshold ΔDT. The relationship between detection threshold and the probability of detections, P_d, or false alarms, P_{fa}, is specific to the type, and knowledge, of the signal and noise being processed. The difference between acoustic target sensing and acoustic communication is that the former involves an unknown signal whereas the latter relates to a known signal.

For acoustic sensing, one derives $P_{fa,S}$ (often in the $10^{-7} - 10^{-12}$ range) from an acceptable number of false alarms over time from

$$\frac{N_{fa}}{\delta t} = 1 - (1 - P_{fa,S})^m, \tag{12}$$

where m is the total number of choices (product between beam numbers, number of frequency bins, ...) made over time δt [8]. For acoustic communications, we relate $P_{fa,C}$ and *BER* (bit error rate) in that a false alarm (i.e., detecting a "signal present" while there is only noise) is analogous of having a bit in error, in that both relate to a binary decision. From this perspective, it is therefore possible to pre-determine $P_{fa,C}$ based on the message length and the impact of a specific *BER*. To use a realistic case based on the NILUS message format [11] and assuming encoding, a 150 bytes message length for reporting a single contact and a $BER \approx P_{fa,C} \approx 10^{-5}$ would lead to approximately one bit in error every 100 messages, which is satisfactory. Other message lengths and $P_{fa,C}$ values can be chosen.

The probabilities of detection, $P_{d,C}$ and $P_{d,S}$, usually are in the $0.3 - 0.9$ range. The $P_{d,C} = P_{d,S} = 0.5$ values are adopted here as they lead to simplifications and correspond to traditional cases in the literature (ref. Assumption (*VI*)), but any other values can be chosen. The rest of the approach is inspired from [8] and assumes extreme cases where acoustic communication occurs with the maximum amount of information about its transmitted signals whereas acoustic sensing operates with the least amount of information about its received signal. Therefore, coherent (respectively, incoherent) processing is assumed for communication (resp., sensing). Assuming $P_{d,C} = P_{d,S} = 0.5$ and a number of samples $n = 2BW \times T$, where $BW \times T$ is the product of the signal bandwidth BW and (integration or symbol) time T, the author of [8] obtains

$$DT_C\ (\text{dB}) = 10\log_{10}\left(\frac{\kappa_C}{2\,(BW\times T)_C}\right), \tag{13}$$

$$DT_S\ (\text{dB}) = 5\log_{10}\left(\frac{\kappa_S}{(BW\times T)_S}\right), \tag{14}$$

where κ_C and κ_S are parameters related to $P_{fa,C}$ and $P_{fa,S}$, respectively. More precisely, κ_C and κ_S relate to the lower integrands (a_C and a_S) of the far-right tail probability integral (assuming normal distributions) as

$$\kappa_C = a_C^2 \text{ and } \kappa_S = (\sqrt{2}\,a_S - \sqrt{(2n-1)})^2. \tag{15}$$

For a normal distribution with $P_{fa,C} = 10^{-5}$, one gets $a_C \approx 4.25$, thus $\kappa_C \approx 18$. Equations (13) and (14) are idealized cases and the reader is referred to Section 13.2 of [8] for a treatment including non-ideal noise characteristics, actual processor, non-perfect sine wave, and additional at-sea losses.

To derive DT_S (or DT_C) of equation (14), the $(BW \times T)_S$ value (or $(BW \times T)_C$) needs to be determined. It can be shown that given any $P_{fa,S}$ many bandwidth-time products $(BW \times T)_S$ lead to -5 dB. Therefore, it is assumed that $DT_S = -5$ dB is maintained by adapting the integration time for a specific frequency bandwidth.

The approach taken to identify $(BW \times T)_S$ cannot be used for determining $(BW \times T)_C$. Indeed, acoustic detections rely on incoherent (or energy) processing whereas acoustic communication uses coherent processing in which the signal phase matters. Coherent processing, in terms of the signal phase, strongly relates to the coherence time of the underwater channel, which is the expected time duration over which the channel response is essentially invariant.

Therefore, equation (13) is expanded as $(BW \times T)_C = BW_C \times T_C$ where we borrow the wideband conclusion of [14] stipulating that $BW_C \approx f_C$, or that the communication bandwidth is of the same order of magnitude than its center frequency. This is equivalent to selecting a transducer with a quality value $Q \approx 1$, that is a non-resonant transducer. For a general transducer, then the relation $BW_C \cdot Q = f_C$ should be used. Moreover, $T_C \leq T_{COH}$ holds as the symbol time cannot exceed the communication coherence time, T_{COH}. An empirical formula of coherence time for both shallow and deep waters is formulated in [21] as

$$T_{COH} = \frac{1}{(\sqrt{2}\,\pi\gamma)\,(f_C * 1000)^{1.5}\,\sqrt{R_C * 1000}}, \tag{16}$$

with T_{COH} (sec.), f_C (kHz), range R_C (km)[1], and from [20]

$$\gamma = 0.6 \times 10^{-10}(\delta c)^2, \tag{17}$$

with δc (m/s) the sound speed standard deviation over the entire water depth. In [21], δc ranges from 0.2 to 0.8. Assuming equation (16) along with the longest symbol time, i.e., $T_C = T_{COH}$, and $BW_C \approx f_C$, one ultimately gets

$$\Delta DT \text{ (dB)} = DT_S - DT_C = -31.2 - 10\log_{10}\left((\delta c)^2\sqrt{R_C\, f_C}\right). \tag{18}$$

3.3.4 Directivity index ΔDI. Recalling that $DI_T = 0$, then $\Delta DI = -DI_T - DI_S + 2DI_C = -DI_S + 2DI_C$. A single, $N = 1$, omnidirectional hydrophone has $DI = 0$, and therefore does not represent an interesting case. Next, we assume a line array with N hydrophones, of length L (m), and with a conventional hydrophone spacing equal to $0.5\lambda_0$. Considering an average sound speed $\bar{c}$ (m/s), the acoustic wavelength of the array is $\lambda_0 = \bar{c}/f_0$, where f_0 is its design frequency. Similarly, the wavelength of a signal of frequency f is $\lambda = \bar{c}/f$. From [2], for unshaded line arrays in look-directions away from endfires, one gets

$$DI \text{ (dB)} = 10\log_{10}\frac{2L}{\lambda} = 10\log_{10}\frac{2Lf_0}{\bar{c}} + 10\log_{10}\frac{f}{f_0}. \tag{19}$$

If the processed frequency is $f \leq f_0$ then the beamwidth grows (thus less precise) as $f_0 - f$ increases, if $f_0 < f < 1.5f_0$ then $DI \approx 10\log_{10} N$, and if $f > 1.5f_0$ then sidelobe amplitudes start dominating over that of the main lobe and $DI = 0$. From equation (19), the first right-hand side term indicates that optimizing DI requires that the product Lf_0 must be as large as possible. Moreover, if $DI \approx DI^* > 0$ is to be maintained over an entire frequency band, then multiple design frequencies or apertures are required. Assuming such designs, then the directivity index simplifies to $DI = -10\log_{10} N^*$, where N^* is the number of hydrophones per aperture. Once applied to sensing and communication, one gets

$$\Delta DI \quad = \quad 10\left(\log_{10} N_S^* - 2\log_{10} N_C^*\right), \tag{20}$$

so that directive communication produces twice the gain of directional sensing for an equal number of hydrophones.

3.3.5 Overall equation $SL_T - SL_C$. Before injecting equations (9), (11), (18), (20) in equation (4), the K_S^* and K_C^* variables will be related to water depth, D (km), as $K_j^* = 2$ if $R_j \leq D$ or $K_j^* = 1$ otherwise where $j \in \{C, S\}$. Using basic logarithmic rules and performing simplifications, equation (4) now expands as

$$\begin{aligned}\Delta SL = SL_T - SL_C = -31.2 - 10\log_{10} f_T^{1.6} + \ldots \\ R_C\,\alpha_m(f_C)\left[\left(\frac{\beta\alpha_m(f_T)}{0.04}\right)^{1.54} f_C^{-2} - 1\right] + \ldots \\ 10\log_{10}\left[\frac{10^{3(K_S^*-K_C^*)}(\beta R_C)^{K_S^*} R_C^{K_C^*-0.5} f_C^{1.1}}{(\delta c)^2}\frac{N_S^*}{(N_C^*)^2}\right],\end{aligned} \tag{21}$$

where the dependent variables are K_S^*, K_C^*. and the independent variables are (with their number in bracket): Environment (2): δc, D; Target (2): f_T, SL_T; Network design (4): R_C, β, f_C, $N_S^*/(N_C^*)^2$. Such explicit dependencies are clearly not present in any of the original SONAR equations. Moreover, equation (21) enables the designer to study, with a single equation, the effects of physical design, network topology, and environmental conditions on underwater nodes performing both target sensing and acoustic communications. As such, there is no equivalent result in the current literature

4 SCENARIO, SIMULATIONS, AND ANALYSIS

Knowing the deployment area means that environmental variables δc and D (or equivalently δc, K_S^*, and K_C^* of equation (21)) can be determined from historical data and charts. For this scenario, environmental quantities are selected as $\delta c = 0.8$ (from [21]) for the sound speed standard deviation and a depth of $D = 0.35$ (km). Also, the network designer must specify the target features (tonal frequency f_T and source level SL_T) as well as the required sensing range, R_S. For this case, target features ($f_T = 0.2$, $SL_T = 130$) are taken from [17] and an arbitrary detection range of 5 km is selected. Through equation (1), knowing both R_S and β leads to R_C, thus reducing the problem to three (3) network design variables: R_C, f_C and $N_S^*/(N_C^*)^2$. To remain realistic, communication source level SL_C cannot exceed 221 dB, which corresponds to the source level used during the Heard Island experiment [9].

Figure 3 shows the outcome of equation (21) for $N_S^*/(N_C^*)^2 = 1$ for which the majority of frequency-range combinations has a source level exceeding 221 dB. The yellow markers in the low source level area indicate the minimum source level for a specific range-frequency combination. Figure 4 captures the fact that the combination of communication range-frequency leading to the lowest value of SL_C follow the power-law relationship: R_C (km) $= 10^{1.9607} \times f_C^{-1.2998}$, with a Mean-Square Error (MSE) of 0.0035 and a coefficient $R^2 = 1$. Figure 4 also contains experimental data extracted from [6] (see CAS, Scripps, SEANet-G3, Develogic HAM, EvoLogics WiSE and UCAC) where $BW_C \approx f_C$, thus matching the current assumption. A more interesting result is in Figure 5 which shows the benefit of increasing the $N_S^*/(N_C^*)^2$ ratio on the lowest source level SL_C. Moreover, design options on the right-side of the dashed black line marking 5 km would mean that a target

[1] Original R_C and f_C units in [21] are in metres and Hz.

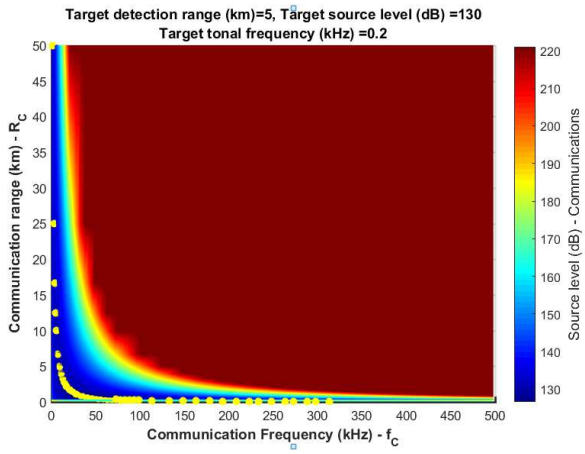

Figure 3: Simulation of equation (21) for specified values

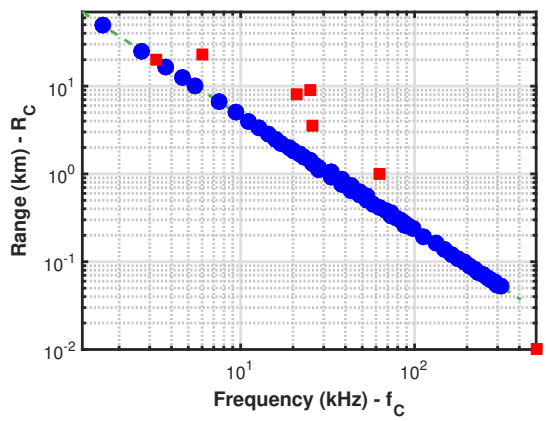

Figure 4: Optimum communication range and frequency leading to lowest source level SL_C based on equation (21). Range and frequency experiments cited in [6].

would pick up an acoustic communication before being detected as $R_C > R_S$. The present analysis holds true except when in presence of ducts/channels, in which case achievable ranges will be much larger and source levels lower. This short-coming is due to the SONAR equation which sees the ocean as a one-dimensional space, thus not accounting explicitly for sound speed variations as a function of depth.

5 CONCLUSION AND FUTURE WORK

This publication proposes a preliminary approach for determining the specifications of a network using acoustic waves for both detection and communication. To the author's knowledge, this is the first time a simultaneous physics-based detection-and-communication network design procedure is proposed. The approach hinges on the conventional and approximate one-dimensional SONAR equation. Despite this simplified approach, the predicted source levels agree well with acoustical communication experiments. In future work, the present approach will be extended to a more rigorous model.

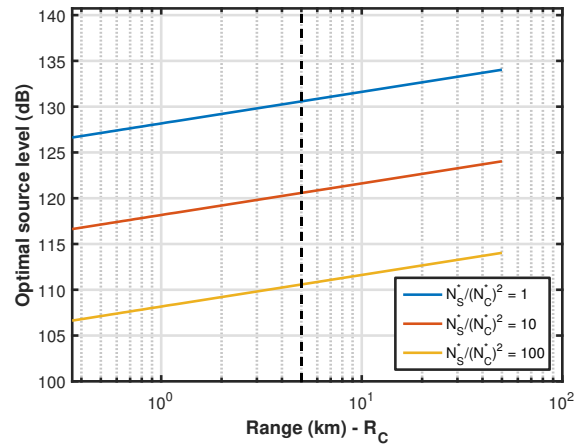

Figure 5: Effect on the optimal (lowest) source level SL_C of the number of hydrophones through the ratio $N_S^*/(N_C^*)^2$ (dashed black line marks 5 km)

REFERENCES

[1] 2003. *Ocean noise and marine mammals.* National Resarch Council.

[2] Michael A. Ainslie. 2010. *Principles of Sonar Performance Modelling.* Springer Praxis Books / Geophysical Sciences.

[3] M. A. Ainslie and J. G. McColm. 1998. A simplified formula for viscous and chemical absorption in sea water. *Journal of Acoustic Society of America (JASA)* 103, 3 (1998).

[4] J. Catipovic, L. Freitag, and S. Merrian. 1991. Underwater acoustic local area network for ROV and instrument communications. In *Proceedings of the AUVS Conference.* 447–460.

[5] M. Chitre, S. Shahabudeen, and M. Stojanovic. 2008. Underwater acoustic communications and networking: Recent advances and future challenges. *Marine Technology Society Journal* 42, 1 (2008), 103–116.

[6] H. S. Dol, P. Casari, T. V.D.Zwan, and R. Otnes. 2016. Software-defined underwater acoustic modems: Historical review and the NILUS approach. *IEEE Journal of Oceanic Engineering* (2016), 1–16.

[7] J. Heidemann, M. Stojanovic, and M. Zorzi. 2012. Underwater sensor networks: Applications, advances and challenges. *Philosophical Transactions of the Royal Society* 370 (2012), 158–175.

[8] R. P. Hodges. 2010. *Underwater Acoustics: Analysis, design and performance of SONAR.* John Wiley & Sons, Ltd.

[9] W. H. Munk, R. C. Spindel, A. Baggeroer, and T. G. Birdsall. 1994. The Heard Island Feasibility Test. *J. Acoust. Soc. Am.* 4, 96 (1994), 2330–2342.

[10] M. Murad, A. A. Sheikh, M. A. Manzoor, E. Felemban, and S. Qaisar. 2015. A survey on current underwater acoustic sensor network applications. *International Journal of Computer Theory and Engineering* 7, 1 (2015), 51–56.

[11] R. Otnes. 2012. NILUS - An Underwater Acoustic Sensor Network Demonstrator System. In *Proceedings of the 10th International Mine Warfare Technology Symposium.* Monterey, CA, U.S.A., 347–352.

[12] R. Otnes, A. Asterjadhi, P. Casari, M. Goetz, T. Husoy, I. Nissen, K. Rimstad, P. van Walree, and M. Zorzi. 2012. *Underwater Acoustic Networking Techniques.* Springer.

[13] R.Coates. 1989. *Underwater Acoustic Systems.* Wiley, New-York.

[14] M. Stojanovic and J. Preisig. 2009. Underwater acoustic communication channels: Propagation models and statistical characterization. *IEEE Communication Magazine* 47 (Oct. 2009), 84–89.

[15] C.M. Traweek and T.A. Wettergreen. 2006. Efficient sensor characteristic selection for cost-effective distributed sensor networks. *IEEE Journal of Ocean Acoustics* 31, 2 (2006), 480–486.

[16] R. J. Urick. 1984. *Ambient Noise in the Sea.* Technical Report. Naval Sea Systems Command, Department of the Navy.

[17] A. D. Waite. 2002. *Sonar for Practicing Engineers* (third ed.). John Wiley & Sons, Ltd.

[18] H. Weinberg. 1985. *Generic Sonar Model.* Technical Report NUSC Technical Document 5971D. Naval Underwater Systems Center.

[19] G. Wenz. 1962. Acoustic ambient noise in the ocean: spectra and sources. *Journal of Acoustic Society of America* 12, 34 (1962), 1936–1956.

[20] T. C. Yang. 2006. Measurements of temporal coherence of sound transmissions through shallow water. *Journal of Acoustic Society of America (JASA)* 120, 5 (2006), 2595–2614.

[21] T. C. Yang. 2008. Temporal coherence of sound transmissions in deep water revisited. *Journal of Acoustic Society of America (JASA)* 124, 3 (2008), 113–127.

DOCUMENT CONTROL DATA

*Security markings for the title, authors, abstract and keywords must be entered when the document is sensitive

1. ORIGINATOR (Name and address of the organization preparing the document. A DRDC Centre sponsoring a contractor's report, or tasking agency, is entered in Section 8.) ACM (Association for Computing Machinery) 2 Penn Plaza, Suite 701 New York, NY 10121-0701	2a. SECURITY MARKING (Overall security marking of the document including special supplemental markings if applicable.) CAN UNCLASSIFIED 2b. CONTROLLED GOODS NON-CONTROLLED GOODS DMC A

3. TITLE (The document title and sub-title as indicated on the title page.)

Simultaneous Design of Underwater Acoustic Sensor and Communication Networks

4. AUTHORS (Last name, followed by initials – ranks, titles, etc., not to be used)

Blouin, S.

5. DATE OF PUBLICATION (Month and year of publication of document.)	6a. NO. OF PAGES (Total pages, including Annexes, excluding DCD, covering and verso pages.)	6b. NO. OF REFS (Total references cited.)
November 2017	5	21

7. DOCUMENT CATEGORY (e.g., Scientific Report, Contract Report, Scientific Letter.)

External Literature (P)

8. SPONSORING CENTRE (The name and address of the department project office or laboratory sponsoring the research and development.)

DRDC - Atlantic Research Centre
Defence Research and Development Canada
9 Grove Street
P.O. Box 1012
Dartmouth, Nova Scotia B2Y 3Z7
Canada

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)
10a. DRDC PUBLICATION NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.) DRDC-RDDC-2018-P075	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

11a. FUTURE DISTRIBUTION WITHIN CANADA (Approval for further dissemination of the document. Security classification must also be considered.)

Public release

11b. FUTURE DISTRIBUTION OUTSIDE CANADA (Approval for further dissemination of the document. Security classification must also be considered.)

12. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Use semi-colon as a delimiter.)

Underwater networks; acoustic detection and communication; simultaneous design; acoustic; detection; communication; sensor network

13. ABSTRACT/RÉSUMÉ (When available in the document, the French version of the abstract must be included here.)

Many papers discuss challenges and solutions pertaining to underwater networks that make use of acoustic waves for either detection or communication purposes. However, no known solution yet exists for jointly conceiving network performing both tasks. This publication proposes a procedure addressing this shortcoming. While considering environmental conditions and physical design decisions, the approach leads to a closed-form expression that has an optimal communication source level solution. Moreover, results compare favorably with experimental data.