FROM SONAR PERFORMANCE MODELLING TO UNDERWATER COMMUNICATION PERFORMANCE MODELLING

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Abstract: *Underwater acoustic communication has been a developing field for the last forty years. Recent advances in embedded computing solutions have been bolstering that development, while advances in underwater robotics have increased the need for this technology. This has resulted in a variety of commercial underwater acoustic modems. Generally, the knowledge of the performance of these systems for the average industrial user is limited to what is advertised in the manufacturer brochures. However, like most other underwater acoustic systems, the performance of underwater acoustic modems is very variable and strongly depends on the environment.*

Fortunately, this has also been an issue for sonar users for the last hundred years. Furthermore, underwater acoustic modems and sonars are both detection and estimation systems, and they also operate in comparable frequency bands.

In this paper, we examine the commonalities and differences between sonar performance modelling and underwater acoustic communication performance modelling. This comparison is done at several levels: requirements of final product, physical processes of interests, and statistical problems. Communication signal processing algorithms are often more complex than sonar algorithms. Integrating them in a performance computation might require actually running them through a simulation rather than representing them by a model.

This paper provides some basic ingredients to design the architecture of a complete underwater acoustic communication performance model.

Keywords: *sonar performance modelling, underwater acoustic communication*

1. INTRODUCTION

In the case of many communication or measurement systems, the expected performance can be accurately represented by a number or a table in a commercial brochure. In the case of underwater acoustic systems, the environmental parameters are often dictating the performance of the system to a point that over-dimensioning the system cannot help compensate for physical effects. In the case of sonar, when the environment is known, computer programs are often used to give a prediction of the operational performance. Such operational tools are in use outside of academia, by government bodies or industries [1-3]. For communication systems, scientific programs can be found that cover a variety of aspects of performance modelling [4-11], but integrated operational tools are not directly available.

In naval operations, knowing in advance how far a unit can detect or be detected, or remain within communication range, is a vital issue. For the offshore industry, predicting the communication range will contribute to the cost estimate of a given operation.

It is not the ambition of the authors to provide a full review of all available or existing tools but rather to provide a high-level overview of the scientific issues.

We propose a top-down approach starting with high level requirements for a sonar/communication performance model, working its way down from the higher to the lower level of a communication stack, identifying quantities of interest and scientific challenges.

1.1. Performance modelling for underwater systems

In Table 1, we propose applications, high level requirements, and available information for performance modelling software for an acoustic underwater system. Sonars and underwater acoustic communication systems make use of the same channel and therefore will make use of the same input for modelling (environmental data), and probably the same acoustic propagation models for a given frequency band. This table is therefore valid for both types of systems.

According to these proposed requirements, a realistic but otherwise synthetic environment is acceptable for the initial design of a system. For this purpose, it is then acceptable to imitate the effect of physical processes on communications, as long as these simulations cover the range of expected effects. Replays of previously measured channel conditions can also be used. This approach, while useful to test the limits of a system, does not allow predicting the performance of a system in a different environment, or relating the performance of the system to specific environmental descriptors (water depth, wind speed, etc.).

Finally, due to the nature of the systems themselves, verification of performance modelling with in-situ data is easier with communications than with sonar, as by definition, two actors in a communication scheme are sufficiently instrumented and cooperative, while in the case of most sonar targets this requires special arrangements (e.g instrumented targets such as echo-repeaters).

Table 1. Underwater performance modelling: high level view of phases and requirements. Most mature topics are shown in green, research topics are shown in red.

	Application	Requirement	Information available
System design and evaluation	Design a functional system for the range of mission environments	Provide a *realistic* representation of a set of communication/sonar environments and the associated performance	Historical oceanographic measurements, previously collected channel soundings. Geo-acoustic information
Preparing a mission (A priori)	Decide mission parameters (number of units, total mission time and area,…) and initial system settings	Provide a *current* representation of the performance in a *specific* environment Estimate the *uncertainty* of the prediction	Oceanographic forecasts
Executing a mission (In Situ)	(Autonomously) Adapt mission parameters and system settings. Assess current performance		Current oceanographic measurements and forecasts Through the system performance measures (Channel soundings, statistics)
After a completion of a mission (A posteriori)	Evaluating and improving the system performance	Reconstruct an *accurate* representation of a specific environment	Oceanographic Hindcasts, Mission measures of performance. System logs

1.2. Sonar performance modelling at a glance

Most sonars are detection systems and are designed to indicate to an operator the presence of a specific set of objects. The location, dynamics and nature of the detected object are generally estimated with various levels of accuracy. The detection process is a probabilistic trial characterised by the probability of detection [12]. The probability of detection is the probability that a target is detected given that it is present and is the quantity generally presented to a sonar performance model user, as a function of target position. This quantity is also indirectly used to provide other information to the user, such as detection range or volume (range, or volume within which a target is detected with a given probability of detection, usually 50%). In a sonar system, detection is based on the comparison of stochastic quantities and false alarms (the erroneous report of a target presence) are bound to occur. Generally, the cost and consequences of a single false alarm are evaluated and used to set a requirement for an acceptable fixed false alarm rate.

We focus on active sonars, as they are most similar to communication systems (detection of a known pulse). The probability of detection, for a given probability of false alarm, is deduced from the predicted statistical distributions of both the target and background (noise and reverberation) signals. These statistics are often based on energies computed by the propagation model, coupled with standard statistical distributions. These predictions can be improved by computing time series [13] and more adapted statistical distributions[14].

Each of these terms is generally computed by a computer model, taking into account the propagation of sound in the water with varying levels of complexity. Depending on the frequency of the sonar, different propagation models are used [1].

1.3. Communication performance modelling

In the case of communication performance modelling, the process is more involved. Networked communication systems are commonly represented by a layered model known as the Open System Interconnection (OSI) stack [15]. The OSI stack is exhaustive and subsets thereof are often used. We present here a very simplified version suitable to many underwater acoustic communication networks, such as that of the RACUN project [16].

The application layer encompasses the protocols specific to an application. We are not considering any specific application in this paper, and we assume that the underwater network can be used for a variety of applications, chosen and parameterised by the user. The user specifies a number of requirements demanded from the network.

The network and media access control layer ensures that information, grouped in units of data known as packets, reaches its destination. There are a variety of network protocols used underwater, [16]. The performance of the network layer, and its capability to fulfil the requirements set by the user depends, amongst other things, on the quality of the point to point links provided by the physical layer.

The physical layer contains the programs and hardware that format and code raw data given up for transmission by the network layer and convert it in a pressure wave by means of a transducer. This layer is also responsible for detecting an incoming acoustic message and providing its contents to the network layer after demodulation and error correction, when possible.

A few observations can be drawn from this enumeration:

- The performance of the underwater communication link depends as much on the physics of the channel as on the individual characteristics and joint performance of a series of software modules and hardware. Quantifying the performance of that link is likely to require the running of these programs (network layer, and demodulation).
- Fortunately, the problem can be at least decomposed between the performance of the physical layer and that of the network layer (which does depend on that of the physical layer).

2. NETWORK LAYER

For a given network deployment geometry and communication protocol, the end user may be interested in the following performance measures:

- The probability of receiving a packet at its final destination (network-*layer packet delivery ratio*).
- The amount of data that can be passed through the network per time unit (*throughput*), either for a single source/destination-pair or in total in the network.
- The expected delay or latency for getting a packet from its source to its destination (*delay statistics*).
- The amount of battery energy used by the communication network (*energy usage*, related to number of physical-layer *transmissions per source packet*)

An end-user can, in particular in the planning phase, also be interested in other questions such as "How many relay nodes do I need between my source and destination to achieve a required level of robustness (*packet delivery ratio*) and throughput, within constraints of maximum delay and energy usage".

Such questions can be answered using network simulations. These are typically run within discrete-event simulation engines incorporating, among other things, an implementation of the network protocol under study and a (simplified) model of the physical layer between different pairs of nodes. In addition to the propagation delay (given by geometry and sound speed), the physical layer is represented by a model of its packet error process.

In network simulations, the *packet error ratio* has often been modelled by combining empirical models for noise and propagation loss with text-book formulas for bit and packet error ratios. This approach assumes that modem performance can be predicted from signal to noise ratio [12] alone, which is not realistic as performance is often limited by delay-Doppler spreading.

For more realistic performance assessments, one first needs to run physical-layer simulations to provide the network simulator with *packet error ratios* for each link in the network. Physical-layer simulation results can for this purpose be stored in lookup tables, with, e.g., *packet error ratio* as a function of range in a given environment.

Another option found in the literature is to replay actual packet error processes from sea trials. This approach can be used if considering the same modem / physical layer as in the sea trial, assuming the trial conditions are representative for the actual deployment.

See [17] for further details and references related to the discussion above.

3. PHYSICAL LAYER

As explained in section 2, the network simulations require the following quantities to be computed for each node link:

- *Delay for every link*: This delay consists of the propagation times between two nodes, which is probably the most straightforward to compute, with a simple propagation model, and that of the modem software and computing hardware (time necessary to encode and decode a given message).
- *The packet error ratio* is the quantity of unsuccessfully delivered packets divided by the quantity of transmitted packets for a given link, at a given instant of time. For a packet to be delivered, assuming a packet is contained within a single modem transmission, it needs to be detected by the receiving modem (process quantified by the probability of detection of a message), and demodulated and decoded without error. Apart from the physics, this is impacted by the design of the modulation, the demodulation program (equaliser and other modules) and the error correction scheme.
- *The energy usage* depends heavily on the hardware used, but also how efficiently the algorithms are implemented and parametrised (number of Doppler channels in a detector, probability of false alarm,…). Furthermore, the transmitter source level also affects the consumption. It should be noted that some of these parameters (for instance source level) can be adapted depending on the outcome of a performance prediction model (or actually experienced performance) to optimise energy usage.

We will first examine how the probability of detection of a message can be computed and how it relates to sonar performance modelling.

3.1. Message detection

Computing the probability of detection of a message is the task for which communication can borrow the most from existing work in sonar research. In many modulation schemes, the communication signal is preceded by a detection preamble, either a linear frequency modulated signal or a more complicated Doppler sensitive signal. Many naval active sonars transmit similar waveforms [18][19] and the theory and recipes to use an acoustic propagation model to compute probability of detection are well documented in literature [12]. Of course many issues remain that are also of interest for communication performance, but these are summarised in section 4.

3.2. Message demodulation

Roughly, two groups of modulation schemes can be distinguished:

Incoherent modulation schemes such as frequency shift keying use energy detection to demodulate the information. The output of an acoustic propagation model, as used for determining the probability of detection, can be used to determine the packet error ratio. Most elements of this approach are described in [20].

The situation becomes troublesome with coherent modulation schemes. There is a bewildering array of such schemes, which have in common that they are sensitive to delay spread and Doppler spread. Performance modelling first requires modelling the delay-Doppler spreading function (which is still an ongoing research topic [5]). At this stage, we are not aware of descriptors of the spreading function which could replace explicitly calculating this spreading function. Furthermore, forward scattered energy of the transmitted modem signal is not only difficult to exploit by the demodulating software, but interferes with the demodulation of the signal [21]. The relevant quantity is the signal to noise-plus-(self-) interference ratio. When the interference term is large, one can draw the analogy with a reverberation-limited sonar system.

Finally, the definition of a modulation scheme is not sufficient to obtain the desired performance indicators, as the design of the demodulator software (equaliser) and hardware (transmitter and receiver spatial and frequential response, etc.) will influence the performance. The definition of what is (usable) signal and what is self-interference will also depend on both modulation scheme and receiver design. Quite often, the complexity of the demodulating software makes it impossible to “model” the performance of the software, the same way the performance of a matched filter or a beamformer can be modelled for sonar.

Another approach is to use the modelled scattering function to generate a simulated signal fed to the modem software and thus compute packet delivery ratio [4]. This approach is also used for generating simulations from measured spreading functions. It is then very useful at the “a priori” stage of communication performance modelling to design and evaluate a (de)-modulation scheme.

Another quantity related to the physical layer that is not directly useful for computing performance of the network layer, but important for system design, or system parametrisation is the channel capacity, which quantifies what is the maximum data rate theoretically attainable in a given channel [22]. This is especially relevant with the advent of more broadband and more efficient transducers (single crystal), as this additional bandwidth might not be supported by the channel. The phase response over this large bandwidth also requires specific attention. At the time of writing of this paper, most suppliers do not seem to provide the phase response of their product and there does not seem to be an international standard for it. Furthermore, there is also a trend to use sonar systems for underwater communications, and interfacing would be facilitated by appropriate standards.

4. DISCUSSION

In this paper, we have brushed over the many topics that concern communication performance modelling and what they have in common with sonar performance modelling. Modelling of incoherent modulation schemes seems to offer the most overlap with sonar performance modelling [20]. Much research has been carried out on simulations based on measurements or an imitation of the real world. A challenging step is to move from simulations based on measurements or real world imitation to a-priori modelling, which requires a better understanding of the physical processes:

The following topics would benefit both the fields of communication of sonar and performance modelling:

- Computation of signal time series instead of only energy [5][6][13]
- Use of appropriate statistical distributions and detection threshold [14]
- Better modelling of the acoustic processes including the effect of the rough surface, including, bubbles and Doppler spread [5][13] and scattering [21]
- Associating a prediction with a measure of uncertainty [23]
- Standardisation of transducer phase response measurements.

Finally, communication performance modelling is a federating discipline bringing together scientists from the field of acoustical modelling, sonar and digital communication. This might be facilitated by the organisation of workshops [24].

REFERENCES

[1] **Etter, P. C.** (2013). Underwater acoustic modeling and simulation. CRC Press.

[2] **Schippers, P., Colin, M. E. G. D., Beerens, S. P**. (2014). The Pieter Schippers story: Almost 40 years of developments in sonar performance modelling in the Netherlands. *UDT, Liverpool*.

[3] **Hjelmervik, K. T., Dombestein, E. M., Mjølsnes, S., Såstad, T. S., Wegge, J.** (2008). The acoustic raytrace model Lybin–Description and applications. *UDT Glasgow*.

[4] **van Walree, P. A., Socheleau, F. X., Otnes, R., & Jenserud, T**. (2017). The Watermark Benchmark for Underwater Acoustic Modulation Schemes. *IEEE Journal of Oceanic Engineering.*

[5] **Dol, H. S., Colin, M. E., Ainslie, M. A., van Walree, P. A., & Janmaat, J.** (2013). Simulation of an underwater acoustic communication channel characterized by wind-generated surface waves and bubbles. *IEEE Journal of Oceanic Engineering.*

[6] **Caley, M. S., & Duncan, A. J.** (2016). Wide-band shallow acoustic channel simulation with realistic Doppler and delay spreading for 3D evolving rough surfaces. *In Underwater Communications and Networking Conference (UComms)*, IEEE.

[7] **Chitre, M., Bhatnagar, R., Soh, W. S.** (2014). UnetStack: An agent-based software stack and simulator for underwater networks. *In Oceans-St. John's, (pp. 1-10). IEEE.*

[8] **Casari, P., Tapparello, C., Guerra, F., Favaro, F., Calabrese, I., Toso, G., ... Zorzi, M.** (2014). Open source suites for underwater networking: WOSS and DESERT underwater. *IEEE Network, 28(5), 38-46.*

[9] **Petrioli, C., Petroccia, R., Potter, J. R., Spaccini, D.** (2015). The SUNSET framework for simulation, emulation and at-sea testing of underwater wireless sensor networks. *Ad Hoc Networks, 34, 224-238.*

[10] **Zuba, M., Jiang, Z., Yang, T. C., Su, Y., Cui, J. H.** (2013, September). An advanced channel framework for improved underwater acoustic network simulations. In Oceans-San Diego, 2013 (pp. 1-8). IEEE.

[11] **Peng, Z., Zhou, Z., Cui, J. H., Shi, Z. J**. (2009, October). Aqua-Net: An underwater sensor network architecture: Design, implementation, and initial testing. In OCEANS 2009. IEEE.

[12] **Ainslie, M.A.** *Principles of Sonar Performance Modeling*. Springer Science Business Media. 2010

[13] **Colin, M.E.G.D., Ainslie M.A., van Vossen R., Prior M.K.**, Influence Of Wind On Matched Filtering Gain In Shallow Water UACE 2015

[14] **Abraham, D. A., & Lyons, A. P.** (2004). Simulation of non-Rayleigh reverberation and clutter. *IEEE Journal of Oceanic Engineering*.

[15] Recommendation, I. T. U. T. X. (1994). 200 (1994)| ISO/IEC 7498-1: 1994. *Information technology–Open systems interconnection–Basic reference model: The basic model.*

[16] **Otnes, R., Asterjadhi, A., Casari, P., Goetz, M., Husøy, T., Nissen, I., ... Zorzi, M.** (2012). *Underwater acoustic networking techniques*. Springer Science Business Media.

[17] **Otnes, R., van Walree, P. A., Buen, H., & Song, H.** (2015). Underwater acoustic network simulation with lookup tables from physical-layer replay. *IEEE Journal of Oceanic Engineering*.

[18] **Doisy, Y., Deruaz, L., Beerens, S. P., Been, R**. (2000). Target Doppler estimation using wideband frequency modulated signals. IEEE transactions on signal processing, 48(5), 1213-1224.

[19] **Jourdain, G., Henrioux, J. P.** (1991). Use of large bandwidth□duration binary phase shift keying signals in target delay Doppler measurements. The Journal of the Acoustical Society of America, 90(1), 299-309.

[20] **Siderius, M., Porter, M. B., Hursky, P., McDonald, V.** (2007). Effects of ocean thermocline variability on noncoherent underwater acoustic communications. *The Journal of the Acoustical Society of America, 121(4), 1895-1908.*

[21] **Jenserud, T., & Ivansson, S.** (2015). Measurements and Modeling of Effects of Out-of-Plane Reverberation on the Power Delay Profile for Underwater Acoustic Channels. IEEE Journal of Oceanic Engineering.

[22] **Hayward, T. J., Yang, T. C.** (2004, November). Underwater acoustic communication channel capacity: A simulation study. In M. B. Porter, M. Siderius, W. A. Kuperman (Eds.), AIP Conference Proceedings (Vol. 728, No. 1, pp. 114-121).

[23] **Abbot, P., Dyer, I.** (2002). Sonar performance predictions incorporating environmental variability. In Impact of Littoral Environmental Variability of Acoustic Predictions and Sonar Performance (pp. 611-618). Springer Netherlands.

[24] **Zampolli, M., Ainslie, M. A., Schippers, P.** (2010). Scenarios for benchmarking range-dependent active sonar performance models. *Ainslie, MA, Validation of Sonar Performance Assessment Tools: In Memory of David E Weston,* 2010