Optimal scheduling for underwater communications in multiple-user scenarios

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LONG-TERM GOALS

One of the long-term goals of this project is to analyze and propose energy-efficient communication techniques for underwater acoustic sensor networks. These techniques aim at consuming as less energy as possible as well as guaranteeing a minimum quality of service. In order to do so, we assume and validate some statistics of the underwater acoustic channels and derive stochastic optimal transmission policies.

Another long-term goal of this project is to investigate the possibility that these underwater acoustic networks disrupt the behavior of surrounding species of marine mammals. As a consequence of these two studies, we aim at developing minimally disruptive communication schemes.

A final long-term goal is to develop the equipment necessary to support current and future envisioned research on undersea VHF acoustic propagation, communication, and networking.

OBJECTIVES

In order to develop the optimal controller that minimizes energy consumption in underwater acoustic communications, we identified the following intermediate objectives:

1. Develop a system model and an optimal transmission scheduler that minimizes the number of transmission attempts in the case where a given amount of packets, B have to be transmitted by a deadline, T. In this case the controller only decides whether or not it is convenient to transmit at a given time.
2. Include in the previous model the cost of transmitting feedback.
3. Include in the optimal controller, as control variable, other communication parameters such as transmission power and redundancy allocation.
4. Analyze the suitability and accuracy of the stochastic model for the underwater acoustic channel assumed in the stochastic optimal controller.
5. Analyze the sensitivity of the proposed solutions to environment-driven non-stationary statistics of the underwater acoustic channel.
6. Propose technical solutions to overcome possible performance degradation of the controller due to changes in the channel statistics.
7. Develop a small, low power, and deployable system for conducting VHF acoustic experiments in the future.

In order to investigate the possibility that underwater acoustic communications disrupt behaviors of surrounding marine mammals, we identified the following objectives:

a   Identify a species that is sensitive to the same frequency ranges used for communications.
b   Quantify the amount of information exchanged among 2 or more animals in different contexts, e.g., while foraging, diving, swimming and in different scenarios, e.g., where there are different social bounds and hierachies.
c   Investigate how they cope with multi-user (and artificial communication signals) interference while vocalizing.

APPROACH

In order to derive optimal stochastic control policies, we make use of the dynamic programming algorithm, which requires to define a dynamic system model, whose evolution depends on both a random process, in our case the channel quality, and a control variable. At each stage, there is a cost associated to the current state and control variable, which is additive with time. The optimization consists in finding the set (called policy) of values of the control variable that minimizes the average total cost of the system evolution. Since we analyze the scenario where a finite number of packets has to be delivered by a deadline T, we only consider the finite-horizon problem. This can be achieved by applying the dynamic programming algorithm. Since such algorithm requires a prior knowledge on the statistics of the random process, we make use of a parametric stochastic model, such as Markov models, to represent the dynamics of the communication performance in time-varying underwater acoustic channels. We plan to validate the suitability of such model, and quantify the sensitivity of such approach. In order to do so, we make use of existing numerical acoustic propagation methods, e.g. Vertex, feed these methods with different environmental conditions (by using oceanographic models), and we perform a statistical analysis on the computed time series of channel impulse responses. After having identified the impacts of each different environmental condition on both the dynamics and features of the channel impulse response, a classifier at the receiver could be used in order to select the most suitable receiving signal processor, which then guarantees the assumed statistics for the communication performance, used by the controller.

By interacting with both bioacusticians and the marine mammal behavioral biologists at WHOI, Saint Andrews University, Duke University, and Scripps, we identified pilot whales as a species of interest in our studies, for the following reasons: i) their communication signals belong to the same frequency bands as that used in artificial acoustic communications, ii) these animals are highly social and use communications to coordinate with each other and maintain network connectivity, iii) they use deep dives (~300-500 m) and in the past such deep divers have been proved to be negatively affected by sonar signals (e.g., mass strandings of Cuvier's beaked whales after sonar operations), iv) numerous data sets containing communication sessions among these animals have been already collected, recently. We tackle the problem of quantifying the information content in a communication session among two or more animals by considering the data sets collected by Prof. Peter Tyack, Dr. Laela Saiygh, and Dr. Frants Jesent, through DTags on long-finned pilot whales in Spain in 2010, 2011, and 2012. These data sets are particularly useful since a small group of related animals was tagged simultaneously and therefore it is easier to reconstruct a communication session, i.e., which animal transmits signals and which receives. This can be done by the comparing the signal amplitude at simultaneous recordings in different tags. From these reconstructed communication sessions, we can quantify metrics, such as network throughput, for different functional contexts (feeding, diving) and social boundings (mum-calf, mum-calf and associated adult, adult-adult). Moreover, by cross-correlating the transmitted and received signals at different tags, we can estimate the arrival time of each message and quantify the interference at each animal, and start investigating their interference management technique.

Following the departure of Dr. Tomasi at the end of her postdoc at WHOI, the remaining funds in the grant were reprogrammed to support the development of a VHF Acoustic Transmission and Data Acquisition to support future research on underwater VHF acoustics, high data rate/short range acoustic communications and networking, and acoustic sensing in the VHF regime.

WORK COMPLETED

We developed a system model for a communication system, where the controller at the transmitter decides whether or not to attempt a transmission based on the dynamic programming solution. The system model included an explicit Markov model for the acoustic channel as parameterized by the packet error rate and time constants for changes in the packet error rate. A cost function which includes the cost of transmitting probe packets to learn the channel state was developed and an algorithm for deriving the optimal scheduler given the cost fuction was developed. We also developed a heuristic scheduling algorithm that has a significantly reduced computational complexity with respect to the dynamic programming algorithm.

During this year we also studied the performance of the designed schedulers when the propagation delays is large enough to accommodate more than one transmission attempt. In such case, the transmitter can attempt the transmission of more than one packet before receiving the corresponding acknowledgment. For this reason, the queue state is known with a delay equal to the number of slots contained in one round trip time. We therefore computed the performance of the schedulers when both channel and queue state information are partial.

We have also evaluated these schedulers over some signals recorded during the KAM11 data set, where channel conditions were not stationary. Finally, we started to tackle the problem of defining a scheduler that decides the coding rate to be used given the channel conditions.

Following the reprogramming of funds, we designed and built the control and receiver portion of a prototype VHF acoustic transmission and data acquisition system. The system will have the capability to support VHF acoustic communications network research in the future to enable realistic communications techniques and networking protocols in the short range/very high data rage regime.

RESULTS

We defined efficient schedulers that minimize the number of transmission attempts while guaranteeing a given deadline. We developed a heuristic scheduler that performs close to the optimal ones but it is also simple to be implemented. We evaluated such schedulers over experimental data (KAM11) and performance curves are similar to the ones derived numerically. Furthermore, we modified these schedulers in order to make them more efficient in the case of long propagation delays. We then focused on the problem of controlling the transmission bit rate (or equivalently modulation or power) over time-varying channels with deadline constraint.

The proposed heuristic scheduler gives rise to a longer battery life-time extension in a lightweight AUV, such as IVER, rather than a heavier vehicle, such as Remus. Up to an hour of battery life-time can be gained for IVER by using the heuristic scheduler compared to the BLIND system.

The control and receiver portion of the VHF Acoustic system have been designed and fabricated, and

initial testing has been completed.

CONFERENCE PAPERS AND TALKS

B. Tomasi, J. Preisig, "Energy heuristic scheduling with partial queue and channel state information", at 2014 ACM Workshop on Underwater Wireless Networks (WUWNet'14), Rome, Italy, Nov. 12 - 14, 2014.

JOURNAL PAPERS

B. Tomasi, D. Munaretto, J. Preisig, M. Zorzi, *Realtime redundancy allocation for wireless channels in the finite blocklength regime*. In Press Elsevier Journal on Ad-hoc Networks.