COMMENTARY

Recent Trends in Underwater Acoustic Communications

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Abstract

Advances in underwater acoustic communications technology are being enabled by more access to in-water data and an infusion of new techniques, researchers and students. In-water data collection is being made possible by robust funding in the U.S., the E.U. and other countries, typically to multi-organization consortia working on both physical and network layer research. At the physical layer, single and multi-carrier modulation methods continue to be refined, with a focus on both low SNR, low-rate, and high SNR, high-rate data links. Establishment of performance metrics for adaptive equalizers and other parts of the physical layer continue, and recent work on high-fidelity channel models that mimic the effects of small-scale ocean processes indicates that progress is being made.

Research in undersea acoustic networks continues to gain momentum as well, with multiple options available for integrating acoustic propagation models with network simulation, providing common frameworks for basing network design. The combination of these recent advances, plus continued interest by maritime science and industry in wireless communications, means that the field is poised to make new commercial breakthroughs in the next several years.

<<H1>>INTRODUCTION

In recent years, there has been a significant amount of activity in the area of underwater acoustic communications, primarily in research but also in development. As the field has matured, several survey articles have been published, addressing the link-level signal processing as well as networking challenges. In December 2008, the IEEE *Journal on Selected Areas in Communications* (JSAC) published an issue on Underwater Wireless Communications and Networks—the first of this kind. Following that, the IEEE *Communications Magazine* devoted its 2009 January feature topic to acoustic communications, and most recently, in January 2013, the *Philosophical Transactions of the Royal Society* published a survey article on recent advances in underwater sensor networks (Heideman et al., 2012). These volumes contain detailed accounts of technical aspects that captured the interest of the research community over the past few years. They also demonstrate that a wider, mainstream communications research community is developing an interest in acoustic communications. Meanwhile, the IEEE *Journal of Oceanic Engineering* and the *Journal of the Acoustical Society of America* continue to be the major sources of relevant information and new results in this area.

Beyond journal publications, topics related to acoustic communications continue to expand at regular venues such as the IEEE/MTS OCEANS Conferences. These topics are also addressed at regular meetings of the Acoustical Society of America (ASA), and specialized workshops are emerging as well. An example is the series of Workshops on Underwater Wireless Networks (WuwNet), which is being organized annually under the auspices of ACM (Association for Computing Machinery), and is currently in its eighth year. In addition, flagship conferences of the IEEE Communications Society and Signal Processing Society, such as Globecom and ICASSP, are starting to organize special sessions and workshops on underwater signal processing and networks. The long-standing Asilomar Conference on Signals, Systems and Computers has had a special session on underwater communications for five years in a row. In other words, the field is flourishing.

Research activities in the U.S. are supported by funding from federal agencies, including ONR and NSF, while in Europe similar organizations are supporting research there. Over the past several years, this funding has made it possible to conduct a number of large experiments, involving multiple research institutions such as the Woods Hole Oceanographic Institution (WHOI) and the Scripps Institution of Oceanography, as well as academia (participants included Arizona State University, University of California at San Diego, University of Connecticut, University of Illinois at Urbana Champaign, Massachusetts Institute of Technology, Northeastern University, and several others. The experiments included the Surface Processes Acoustic Communications Experiment (SPACE 2008), the Mobile Acoustic Communications Experiment (MACE 2010) (Figure 1), and the Kauaii Acoustic Communications Experiments (KAM 2008 and 2011), which took place in the U.S. In Europe, major experiments took place in Norway, Italy, and several other countries. Researchers in Singapore, Norway, Germany, Italy, Spain, The Netherlands, and Portugal have also actively contributed to the increasingly international acoustic communications scene.

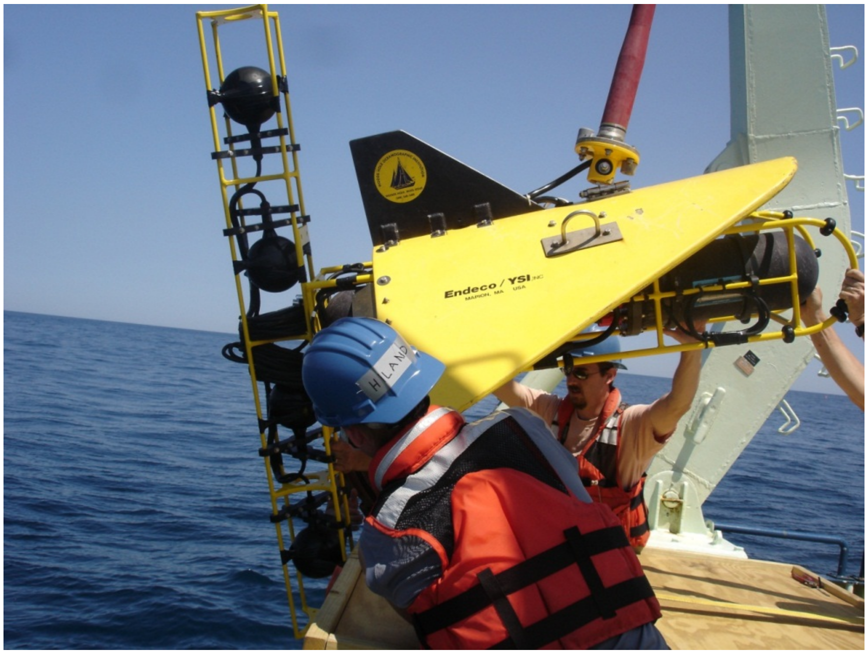

Figure 1. A tow fish with a four-element vertical source array is deployed on the *R/V Oceanus* during the MACE 2010 cruise south of Cape Cod, MA.

The availability of large experimental data sets is important for advancement because of their realism compared to models. However, the importance of models is growing as their fidelity improves and they become more realistic. A special workshop, organized by the NATO CMRE in Italy in September 2012, drew participants from all over the world to discuss the topic of acoustic communication and channel modeling, which is critical to standardizing performance evaluation and reducing the need for costly field experiments. Selected papers from that meeting will soon be published in a special issue of the IEEE *Journal of Oceanic Engineering*.

The growth that the field of underwater communications is experiencing has also led the community to realize that this topic cannot, and should not, be considered as a stand-alone one, separate from a much larger body of research that is evolving in parallel in the fields of navigation, localization, vehicular robotics, and system integration in general. The push has thus been for an interdisciplinary approach to research that will tackle complex problems of autonomous underwater systems. Such cross-cutting research is increasingly being promoted by the funding agencies (Edwards, 2013), and researchers are responding. Examples are evident in recent publications that address complex system optimization involving multiple vehicles that have to operate in a collaborative manner while sharing the limited acoustic bandwidth (Hollinger et al., 2012), or network relay systems dedicated to efficient image transmission (Murphy et al., 2013).

In what follows, we will focus our attention on summarizing the key components of acoustic signal processing that have emerged in the past few years and that define current research trends in this area.

<<H1>>**SIGNAL PROCESSING FOR COMMUNICATIONS**

The past several years have seen a number of interesting developments in signal processing for communications, whose common goal is to increase the data rate and improve the performance of communication over band-limited acoustic channels. While the question of acoustic channel capacity remains open, these practical techniques have been steadily pushing the limits of traditional system design, to adapt it to frequency-selective and highly Doppler-distorted acoustic channels. Specifically, work has been active on single-carrier as well as multi-carrier modulation/detection techniques, and the attendant issues of adaptive channel estimation/equalization, multi-input multi-output (MIMO) signal processing, and adaptive modulation methods.

<<H2>>Single-Carrier Modulation and Detection

In the realm of single-carrier modulation/detection, significant advances have been made by using adaptive turbo equalization techniques (see Choi et al., 2011 and references therein). These techniques capitalize on combining channel coding and equalization to improve the system performance. Unlike the conventional equalization techniques, which form the backbone of existing acoustic modems and in which channel coding is treated separately from equalization, turbo equalization techniques are based on the idea of concatenated coding, where the outer code is applied at the transmitter, while the channel plays the role of the inner code. The receiver design is based on iterative decoding, which must also incorporate adaptive channel estimation. The underlying signal processing is quite complex, and the major research thrust has been on developing manageable-complexity receiver algorithms and improved channel estimation techniques. Cast in a MIMO framework, these techniques have shown substantial performance improvement over the existing systems (an order of magnitude or more reduction in the bit error rate at 15 kbps in 9 kHz of bandwidth is reported in (Choi et al., 2011).

Another technique that has shown promise for equalization of single-carrier broadband systems on channel with extended multipath is that of partial response equalization (Roy et al., 2009). In this technique, the channel is first partially equalized to a shorter, a priori set response, and then subject to further decoding.

Crucial to successful equalization is adaptive channel estimation, and recent work has recognized that although the acoustic multipath is long, it is often sparse (Figure 2), and this can be exploited to improve channel estimation. Sparse channel estimation disposes of the traditional minimum mean squared error (MMSE, or norm-2) optimization, and focuses instead on constrained norm-1 or mixed-norm minimization as a computationally feasible approximation to the (norm-zero) problem of sparse channel estimation. While the literature offers a wealth of sparse estimation algorithms, in single-carrier equalization, sparse channel estimation has recently been addressed in (Pelekanakis & Chitre, 2013).

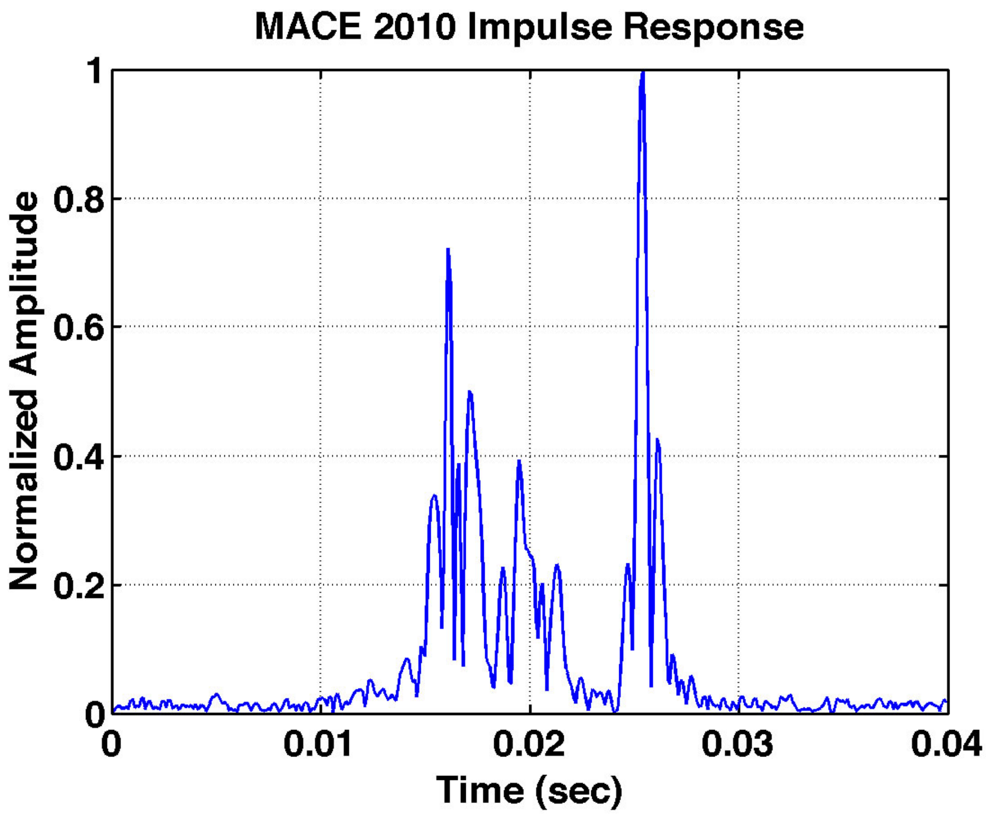

Figure 2. Multipath measured during the MACE 2010 experiment during one of the source tows.

A special method that has long been used in conjunction with single-carrier equalization is time-reversal (or phase conjugation in the frequency domain). Applied either actively (at the transmitter) or passively (at the receiver), a time-reversed replica of a received signal waveform is used to implement a filter matched to that waveform, thus aiming to optimize the input to the equalizer. Recent results in this area include (Cho et al., 2011), which extends previous work to a multi-user framework, applying time-reversal not only for equalization, but for interference cancellation as well.

<<H2>>Multi-Carrier Modulation and Detection

An alternative to single-carrier modulation/detection techniques are multi-carrier techniques, typically implemented in the form of orthogonal frequency division multiplexing (OFDM). While routinely used in many terrestrial systems (DSL, WLAN, Digital Audio/Video Broadcast, LTE, and standardized for the 4G cellular systems) OFDM has only recently begun to emerge in the acoustic world (Li et al., 2008). Recent years have seen a plethora of results, which attest to the fact that OFDM is a viable low-complexity alternative for combating the frequency-selectivity of the acoustic channel. By virtue of dividing the frequency band into many narrow sub-bands, each of which can be treated as frequency-flat (nonselective), OFDM allows for simple FFT-based equalization; it is conducive to MIMO implementation for spatial multiplexing or transmit diversity gain, it supports differentially coherent detection, and easily lends itself to adaptive modulation. Its major drawback, however, is the sensitivity to the time variation of the channel, which causes intercarrier interference (ICI). This problem has been the focus of recent research, and several techniques have been developed to address it. They include ICI equalization via augmented sparse channel estimation (Berger et al., 2010), recursive ICI equalization (Tu et al., 2011), and pre-filtering methods based on multiple-FFT demodulation (Aval & Stojanovic 2012). All of these methods have been demonstrated using in-water data, showing good performance in varying channel conditions (e.g. Aval and Stojanovic 2012 reports on transmitting at 9 kbps over a 5 kHz mobile acoustic channel with a multi-hour average mean-squared detection error below −9 dB).

The quest for high-rate transmission over acoustic channels is tightly coupled not only with the receiver's ability to adapt to the changing channel, but also to the ability to feed the channel state information back to the transmitter, so that it can adapt to the environment as well. While conceptually simple, the ideas of adaptive modulation are not nearly as easy to demonstrate in practice, as they require on-line experimentation. In reference (Radosevic et al., submitted) reports on one of the first attempt to do so. Specifically, it focuses on multi-carrier modulation, where both the modulation level and the signal power can easily be adjusted for each of the carriers. Two types of feedback-based power control are used, one that adjusts the total power level, and another one that distributes it across the signal spectrum (carriers).

Future work on signal processing for acoustic communications will likely focus on improving our understanding of the channel distortions, so that they can be targeted in an efficient manner. Research trends will focus not only on conventional point-to-point links, but also on multipoint-to-point links (in multi-user or co-operative communications frameworks), interference-limited regimes (links with unintentional or intentional interference), low probability of intercept/detection (LPI/LPD) systems for secure communications, and others. Feedback-based methods, by which the receiver can inform the transmitter of its current state, are likely to draw attention, as they offer large potential gains through adaptive power and rate control. Understanding of channel distortions and classification of channel parameters into those that can be predicted, those that can only be estimated, and those that are intractable, remain important research tasks.

<<H1>>CHANNEL AND NETWORK MODELING

The need to investigate adaptive modulation methods, as well as network protocols which cannot be analyzed using off-line experimental data, but require in-situ experimentation, has sparked a renewed interest in channel modeling. Channel modeling, and in particular statistical channel modeling, is necessary for the development of channel simulators, which will aid in such analyses. While these simulators cannot replace experimental trials, they are expected to help in preparation for the (costly) deployments.

Ray tracing codes such as the Bellhop model (see reference list) are now in regular use for estimating the nominal channel characteristics (Figure 3), but they were not designed to simulate the random channel effects caused by small disturbances. Such disturbances result from the displacements of transmitter/receiver and the channel boundaries, and other environmental changes including those caused by tides, currents, and wind-driven surface waves. The motion-induced Doppler effects have been addressed in a computationally more efficient manner by the VirTEX simulation algorithm (Peterson & Porter, 2012). The effects of the surface waves curvature, and the amplitude and arrival time fluctuations that they introduce, have been modeled in (Deane et al., 2012). A statistical approach to channel modeling is taken in (Qarabaqi & Stojanovic, in press), where micro-multipath caused by surface scattering is modeled as a complex-Gaussian multiplicative distortion imposed on each surface-reflected path, with path-specific, frequency-dependent correlation. While much remains to be done on the subject of acoustic channel modeling for communications, the topic has clearly captured the attention of the research community and we are likely to hear more about it in the future.

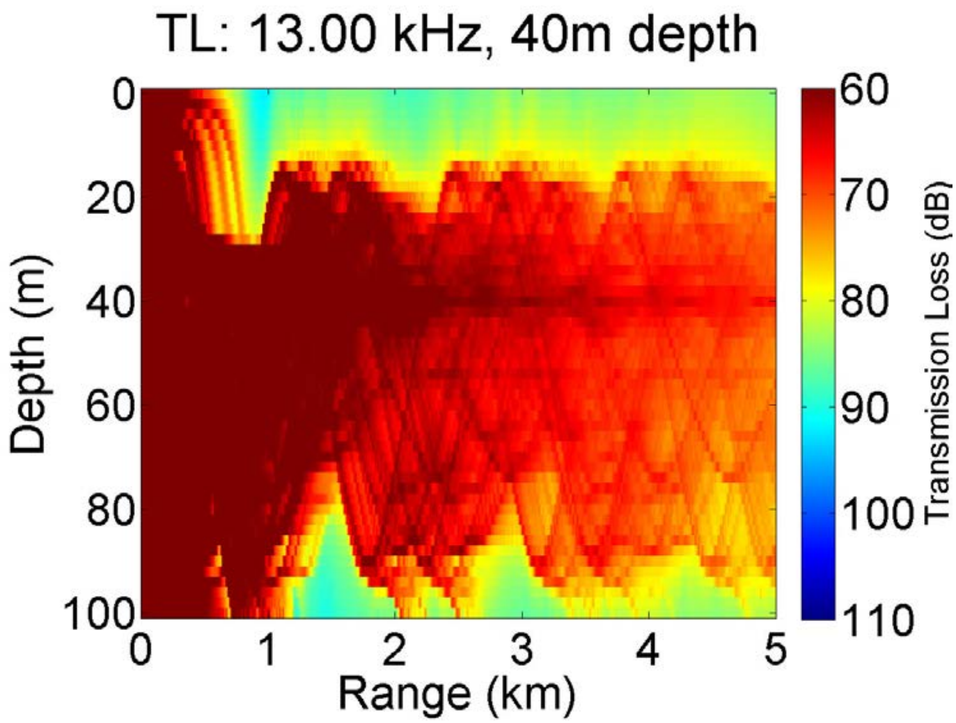

Figure 3. Transmission loss computed using the Bellhop model for the sound-speed profile observed during the MACE 2010 experiment.

In parallel with the work on physical channel modeling, several efforts have been underway to develop network-level simulators. See Heideman et al. (2012) for an overview of recent activities in acoustic networking. In addition to implementing a suite of communication network protocols, these simulators typically employ a ray trace algorithm, coupled with digital ocean maps so that a user can specify the desired location and system geometry. Basic effects of acoustic signal delay, frequency-dependent attenuation and noise are thus included in a network simulator. Inclusion of time-varying channel effects remains to be addressed as relevant physical-link models emerge. Two frameworks that stand out are SUNSET, from Sapienza University, and DESERT Underwater from the University of Padova (see links in the reference list). Both projects include multiple investigators and collaborators and build upon the ns2 or ns2 MIRACLE network simulators.

<<H1>>CONCLUSIONS

The continued appearance of acoustic communications research in mainstream signal processing and communications publications (in addition to ocean and acoustics-related journals) supports the contention that the area is rich enough technically to attract talented investigators from diverse academic backgrounds. The growth of student participation, manifested by completed Masters and PhDs, plus a strong showing in posters at major conferences, also heralds the continuation of work by a new generation of researchers.

The recent advances, described so briefly here, are likely to be significant because of the rigor in the approach and the use of both in-water data for field trials, and the inclusion of simple propagation models that at least include shadow zones and demonstrate that range is not the only important parameter. As higher-fidelity models (combining measured statistics and propagation) are made available to the community, standardization of methods for benchmarking algorithms will become more prevalent, allowing easier identification of significant advances. Reporting of both field results and computer simulations in terms of parameters such as the SNR at the input to the receiver, will make comparison and extrapolation much easier.

Ultimately, the undersea technology market will drive the investment in specific new physical layer and network techniques. While the first-generation "killer application" for underwater telemetry—communicating with and controlling an AUV—is reasonably well-satisfied by existing technology, many improvements could be made. However, demand for hardware remains modest compared to consumer electronics, and the level of investment necessary to move from a laboratory prototype to real-time and ready-for-sale, is high. Further, the more sophisticated the solution, the more expensive the implementation.

Better modeling, new development tools, increased access to the sea for realistic data and the emergence of new demand could change the situation quickly. The research field has reached a transition point, and the question really is, how long before development and application catch up?

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