Telemetry and the Underwater Channel: Progress and Challenges

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Abstract: Advances in underwater acoustic telemetry since 1982 are reviewed and evaluated in terms of their contribution to increased data rates and ranges. A great deal of research may be discussed in the framework of five major areas: coherent signaling, adaptive equalization and carrier recovery, error control coding, spatial and frequency diversity exploitation, and networked systems. Many published telemetry systems are concisely compared in a performance space of data rate and range. Finally, a view of the challenges facing the community in the years to come is presented.

TELEMETRY SYSTEMS CIRCA 1982

The Digital Acoustic Telemetry System (DATS) was among the first of a generation of systems seeking reliable digital transmission of information at modest data rates (1). Using an incoherent modulation scheme of multiple frequency shift keying (MFSK), data rates of 400 – 1200 bits/sec were achieved with an average error probability of $10^{-1}$. 10 KHz of bandwidth was consumed, however, by the frequency hopping leading to bandwidth efficiency characteristic of incoherent systems. Other features included error protection in the form of an (8,4) Hamming code, separate time and doppler synchronizations, and a steerable phased array with a 5 degree beamwidth. Performance was demonstrated in the adverse channel found in Woods Hole Harbor. Other incoherent systems then and since generally share the features of robustness and modest data rates exhibited by DATS. At least two systems funded today by the ONR are based on similar principles. The challenge facing engineers 15 years ago was to design systems offering acceptable reliability at higher data rates and ranges.

TELEMETRY SYSTEMS CIRCA 1998

The literature since 1982 is replete with reports of underwater acoustic telemetry system performance, particularly since the ascension of coherent systems in the early 1990's. A useful metric for comparison is a performance space defined by data rate and range. Figure 1 depicts a compilation of 26 published modem results. In view of the differing demands imposed by shallow and deep water channels, summaries are segregated on that basis.

![Figure 1](image-url)  
**FIGURE 1.** Survey of 26 acoustic modems in published literature from 1985 to 1996. The left panel groups results for shallow water channels together while deep water systems are depicted in the right panel. As a reference, the DATS modem and others of its class generally operated around the large X seen in the left panel.
CLASSIFYING THE PROGRESS AND CHALLENGES

Perhaps the single most important development has been the successful use of coherent modulation methods. The prevailing paradigm in 1982 was that medium fluctuations were too rapid to permit carrier phase recovery. The application of jointly optimum adaptive phase synchronization and equalization made possible by great strides in computational capabilities demonstrated coherent modulation in a wide variety of underwater channels (2). Notably absent from that research was a careful consideration of the physics of ocean channels and the implications for coherence. Obtaining that understanding is the primary challenge facing attempts to expand the breadth of channels supporting coherent modulation. By exploiting the powerful modeling capability present in the ocean acoustic community, more accurate predictions of propagation, scattering, and noise processes may be brought to bear. Additionally, real-time characterization in the form of in-situ channel probes will allow optimum selection of telemetry system parameters. For example, one modem currently being developed by the Woods Hole Oceanographic Institution (WHOI) probes the channel periodically to estimate an impulse response which governs the selection of a number of receiver parameters. Alternatively, direct predictions or measurements of the channel scattering functions will allow more classical communication system design principles to be invoked. Understanding the interplay between complexity of the receiver and variability of acoustic propagation remains a formidable challenge for the community.

Many of the proposed designs trade complexity for performance in four categories. First, the equalizers are either linear transversal filters or decision feedback equalizers (DFE). Second, the update algorithm is either a stochastic gradient descent or recursive least squares (RLS) with RLS offering faster convergence with higher complexity. Third, multi-channel processing generally takes the form of classical beamforming, diversity combining, or a multi-channel DFE. Finally, carrier recovery is accomplished by the equalizer or an explicit phase-locked loop (PLL). The most successful architectures are multi-channel DFE-RLS-PLL combinations at the cost of high complexity. Three challenges face further receiver development. Firstly, ways of reducing complexity while maintaining performance are needed for operation in highly spread channels. Secondly, explicit platform motion compensation will relieve the equalizer tracking burden particularly in autonomous underwater vehicle (AUV) applications. The integration of such strategies into the receiver is a key element of their performance. To move beyond the question of whether a coherent receiver will work to when it will work requires more extensive experimental validation than is generally evident in the literature today. Receiver architectures will remain a research focus in the years to come.

Both spatial and frequency diversity has proven to be quite effective in increasing system performance margins. Most investigations have taken an empirical approach to evaluating diversity by designing particular receivers and reporting on their effectiveness. Multipath coherence at telemetry frequencies is not well quantified. Filling this knowledge gap is a principle future challenge. The stability of adaptive multi-channel combining algorithms in a real, dynamic underwater channel is equally uncertain, primarily due to a poor characterization of those dynamics. Once again, a close coupling to the ocean physics may provide the key to better performance.

The promise held out by information theory is that both source and channel coding provide a fundamental tool in increasing transmission rates and reliability. Channel coding for incoherent systems has been closely examined in the years since 1982. Source coding, primarily for the image compression application, is a vigorous area of current research. Channel coding for coherent systems, however, may well pose a substantial challenge primarily due to the prevalent use of DFE-based approaches requiring an integrated approach to decoding and equalization.

Finally, research in underwater acoustic networks is increasing in recent years as a result of increased interest in distributed sensor architectures. The conventional strategies for multiple-user access including time division multiple access (TDMA), frequency division multiple access (FDMA), and code division multiple access (CDMA). All face unique difficulties in their application to underwater telemetry channels. Innovative developments in network protocol may well be required.

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