Proceedings of the Seventh European Conference on Underwater Acoustics, ECUA 2004
Delft, The Netherlands
5-8 July, 2004

HIGH-RATE PHASE COHERENT ACOUSTIC COMMUNICATION: A REVIEW OF A DECADE OF RESEARCH AND A PERSPECTIVE ON FUTURE CHALLENGES

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Slightly more than 10 years ago the Woods Hole Oceanographic Institution and Northeastern University published a new algorithm for multi-channel adaptive equalization along with results of using that algorithm to successfully decode long-range, high-rate, acoustic communication transmissions. In the years since the authors have built on this foundation to improve and adapt the core algorithm for different acoustic environments and applications, incorporating Doppler compensation, selectable filter update algorithms, and error-correction capability. The resulting structures are used as the core for receivers operating in a multi-user environment, and for reception of multiple, simultaneous data streams in a MIMO environment. Significant challenges remain, in particular, selection of equalizer parameters (for example, the number of filter taps) based on acoustic channel conditions to optimize receiver performance in a time-varying environment. New approaches to receivers include channel estimation with the goal of both faster adaptation and receiver parameter self-optimization.

1. INTRODUCTION

The late 1980s and early 1990s saw an increased interest in underwater acoustic communication in support of fixed oceanographic instrumentation and the fledgling autonomous underwater vehicle development community. In the intervening years AUVs have indeed come of age, and high-speed data upload from remote instruments has become a reality. Work has continued throughout the 1990s to the present on faster and more robust acoustic communications systems, with continued interest in bandwidth-efficient single-user links, augmented by research in multi-user systems to realize the promise of underwater networks. Four review papers, by Baggeroer [1], Catipovic [2], Stojanovic [3], and Kilfoyle/Baggeroer [4] respectively, provide a broad view of the field's history, and thus in this paper we instead focus on the development path and varied application of the multi-channel DFE with integrated PLL and jointly adapted coefficients. This structure, first introduced in 1993 [5] and 1994 [6] by Stojanovic, Catipovic, and Proakis, is used as the core of a number of subsequent developments, including multi-user receivers and spatial-modulation to name just two examples.

The paper is divided into two sections, the first a review of the authors' work that is a direct out-growth of the 1993 and 1994 publications, and the second an introduction to two areas of current interest, receivers which employ channel estimation, and transmitters that modulate multiple data streams on multiple transmit elements, typically referred to as multi-input, multi-output (MIMO). The review of the DFE includes discussion of the many-to-few reduced-complexity receiver, Doppler compensation and phase-tracking, integrated error-correction coding, sparse equalization, and system optimization under widely-varying acoustic propagation conditions. The review motivates a short discussion of channel-estimation receivers and MIMO systems, and the paper concludes with a discussion of some of the challenges that remain and thoughts about new directions that may prove fruitful.

2. THE EARLY YEARS AND INITIAL APPLICATIONS

The original experiments designed by Catipovic, Stojanovic, and Proakis and carried out by WHOI in the Pacific in deep water, and in the Atlantic on the continental shelf, obtained very high quality data through careful selection of high-power, broadband acoustic sources, use of multi-channel receivers, and transmission of signals with high-density constellations using the widest possible bandwidth. These two experiments, along with others conducted in shallow water near Woods Hole, provided a rich data set with varying channel spread and SNR, though relatively low Doppler due to the modest source-receiver motion created by drifting vessels. These data were used to demonstrate several significant communications links, including: 660 bps at 200 km in deep water in the Pacific, 2000 bps at 90 km on the Atlantic continental shelf, and 10k bps at 3 km in shallow coastal water [6].

The receiver used to achieve these results was the decision feedback equalizer with 2nd order PLL. The results were further improved shortly thereafter by development of a reduced-complexity receiver that includes a novel many-to-few stage that combines multiple hydrophones with complex-valued weight vectors and presents these combined outputs to the standard DFE [7]. A primary feature of this approach is that the solution is jointly optimized: the combiner and equalizer filter coefficients are updated using a single error estimate. When the processor was applied to the same data sets, improvements of up to 6 dB in SNR at the output of the receiver were achieved with minimal increase in computational complexity.

Based in part on these positive results and the desire to demonstrate real-time acoustic communications with an AUV, in 1995 DARPA sponsored a program that required development of acoustic communications receiver system that could operate autonomously [8]. This required another phase of work that included Doppler estimation and compensation [9], automatic setting of filter tap widths, and sparse equalization to include long-delay arrivals, all of which had to happen in near real-time on an AUV. The program was ultimately successful, paving the way for a follow-on program that included transmission of image segments in real-time from an AUV [10], and an Advanced Tactical Demonstration described in [11-12], now part of an on-going Navy transition program.

As the algorithms that are used for these applications have matured, certain approaches to initialization, for example, setting the number of taps in the feedforward filters, have been done using unpublished, ad-hoc approaches. While these non-optimal approaches do presently work, an important area of research continues to be automatic setting of filter lengths and the subsequent adjustment of forgetting-factors or learning rates of the adaptive filter algorithms such as RLS or LMS. One of the goals of channel estimation based equalizers described below is to incorporate at least some of the channel adaptation needs into the core of the receiver to avoid use of an ad-hoc pre-processing stage.

Additional applications of the multi-channel DFE that have proven effective include its use in a multi-user environment. Work in this area was initially done by Stojanovic and Zvonar [13], later by Stojanovic and Freitag [14], and also extended by Kilfoyle for reception of parallel data streams in a MIMO environment described later. In the Stojanovic/Freitag case the DFE is operated in a mode where the block codes used for error-correction are decoded when sufficient symbols become available, and after decoding each block, the surmised transmitted bits are fed back to update the equalizer filters. Thus the DFE can be operated below the SNR typically required to avoid the catastrophic error propagation that occurs when incorrect symbols are fed back, which increases its usefulness in low SNR applications as well.

3. CHANNEL ESTIMATE BASED EQUALIZATION

Channel estimate (CE) based equalizers use observations of the received signal to estimate the channel impulse response and possibly the statistics of the interfering noise field in order to calculate the equalizer filter coefficients. This may be done with different goals in mind, the two primary objectives typically being either reduced computational complexity or reduced mean squared error, and ideally both. While there is no single optimal channel estimation receiver, variants that are based on the DFE show considerable promise because they improve on linear equalizers while allowing complexity reduction by identification of the filter taps that are worthy of updating. The reduced complexity version is presented in [15], and some recent work on comparing different CE equalizers is described below.

Specific examples include channel estimate based decision feedback equalizers (CE-DFE), linear MMSE equalizers (L-MMSE), and Passive Time-Reversal equalizers (P-TR) [16]. The performance of the different equalizers may be compared using the mean squared error, which is made up of the minimum achievable error and the excess error. The former is the soft decision error that would be realized by the equalizer if the filter coefficient calculation were based upon perfect knowledge of the channel impulse response and statistics of the interfering noise field. The latter is the additional soft decision error that is realized due to errors in the estimates of these channel parameters. Analysis of the performance of these three types of equalizers [17-19] shows that the CE-DFE has a lower minimum achievable error than both the P-TR equalizer and the L-MMSE equalizer. However, for equalizers with the same number of taps in their feedforward filters and using the same channel and interfering noise estimates, it can be shown that the excess error is proportional to the norm squared of the equalizer's feedforward weight vector. For the region of a large adaptive processing gain, norm squared of the CE-DFE feedforward filter weight vector will be larger than that of both the P-TR equalizer and the L-MMSE equalizer. This sensitivity of the CE-DFE to channel estimation errors has motivated additional work on the development a channel estimate based decision feedback equalizer that maintains its excellent performance when using good quality channel estimates while at the same time improving its performance when using poorer quality channel estimates.

Stojanovic, et. al. [20] showed that the impact of channel estimation errors could be modeled as an increase in the level of the observation noise and suggested increasing the assumed variance of the observation noise to improve the performance of a CE-DFE in the presence of channel estimation errors. Preisig [19] has developed an equalizer termed the Residual Prediction Error DFE (RPE-DFE) that advances this idea even further. The RPE-DFE exploits the fact that the residual prediction error of the channel impulse response estimation algorithm is the sum of the observation noise plus additional unmodeled signal due to the algorithm's error is estimating the channel impulse response. This residual prediction error is used to estimate the statistics covariance matrix (as opposed to just the observation noise) of an effective observation noise and this estimated covariance matrix is used when calculating the optimal DFE filter coefficients.

Preliminary results with a three-channel equalizer in a rapidly varying shallow water channel have shown that a CE-DFE with the traditional assumption that the observation noise level equals the observed noise in the received signal behaves much worse than the two other approaches. The CE-DFE with the assumed observation noise level increased to compensate for channel estimation errors as suggested in [20] is 6 dB better than the traditional, and the RPE-DFE offers another 1 dB improvement.

4. SPATIAL MODULATION

Exploitation of the ocean’s rich spatial structure may provide the next step in significant bandwidth efficiency gains in channels with significant inter-symbol interference. Spatial modulation seeks to use multiple, resolvable propagation paths between two arrays to create, in effect, parallel independent communication channels within the single, physical ocean channel. The benefits are completely analogous to those of increased bandwidth. Just as independent access to the in-phase and quadrature components of a communications signal led to improved bandwidth efficiency, spatial modulation can make additional, orthogonal signaling dimensions available. By use of appropriate spatio-temporal filters with both transducer and hydrophone arrays, multiple channels are realized. Several aspects of spatial modulation in the underwater acoustic channel are discussed, including optimal modulation techniques, an effective extension of the canonical DFE/PLL equalizer to demodulate such signals, experimental results to date, and current research trends.

The issue of how to map an information stream onto a transmit array is a rich area of current research in the wireless radio frequency industry and is only recently receiving attention in the context of underwater telemetry. Many older approaches to spatial modulation for MIMO channels use a singular value decomposition of a known channel transfer function matrix [22]. Recent approaches suggest various mappings of coded and uncoded data streams to the available transmitters, such as [23], and generally assume the channel transfer function is comprised of uncorrelated Rayleigh random variables. The design of a practical system for MIMO channels requires striking a balance between efficient power transmission, acceptable interference between the sub-channels, and realistic channel state feedback requirements. Using a physical channel model as motivation, a new class of MIMO channel design strategies has been developed that optimize power-based metrics [24] appropriate for the UAC. Recent experience suggests channel feedback is important for underwater applications.

The DFE/PLL has been shown to be well suited for the dispersive conditions in the UAC. An effective receiver for spatially modulated signals would, therefore, spring from that foundation. The multi-user version of the DFE/PLL presented in Stojanovic and Zvonar [13] is a suitable structure with two important modifications. First, the “users”, in this case, derive from the same information stream, so the receiver structure includes a Viterbi decoder that accommodates source-coding dependencies between the individual signal streams and provides coding gain to the filter update process. Second, the decision feedback filter is extended to include taps for the current symbols of all the data streams. The feature is particularly important if the channel gains for each data stream vary significantly such as with near-far behaviour.

As an example of what is possible using spatial modulation, one of the results from a recent set of sea trials near Elba, Italy, showed over a three-fold increase in estimated UAC capacity [25]. The channel was ISI limited in this case and simply increasing power would not have enabled higher data rates. A six-element transducer array was used to send from one to six independent data streams having identical waveform descriptions over a 2.5 km range to a 14-element receiver array. By assuming the equalizer whitens the residual noise, the output SNR from the equalizer can be used to estimate the channel capacity, C. While the system could create a single data stream with 23.5 dB SNR going into the decision device, spatial modulation supported four streams of about 14 dB SNR, a marked improvement.

Application of spatial modulation to the UAC is far from a mature research area. Many directions remain to pursue including channel state feedback experiments, array topology optimization, and real-time implementation in, for instance, an underwater network. Nonetheless, much promise has already been demonstrated suggesting spatial modulation will play a key role in underwater telemetry applications demanding high data rates.

5. ACKNOWLEDGEMENTS

This work was funded by the Defense Advanced Research Projects Agency and the Office of Naval Research through many programs from 1990 through the present. The contributions of Josko Catipovic, John Proakis, Geir Sandsmark, Mark Johnson, David Brady, and many others have all made this work possible.

REFERENCES

[1] **Baggeroer, A.** Acoustic Telemetry—An Overview, *IEEE J. Oceanic Eng*. **9**, pp. 229-235, Oct. 1984.

[2] **Catipovic, J.** Performance Limitations in Underwater Acoustic Telemetry, *IEEE J. Oceanic Eng*. **15**, pp. 205-216, July 1990.

[3] **Stojanovic, M**. Recent Advances in High-Speed Underwater Acoustic Communications, *IEEE J. Oceanic Eng*. **21**, pp. 125-136, April 1996.

[4] **Kilfoyle, D. and A. Baggeroer**, The State of the Art in Underwater Acoustic Telemetry. *IEEE Journal of Oceanic Engineering*, **25**(1): p. 4-27, 2000.

[5] **Stojanovic, M., J. Catipovic, and J. Proakis,** Adaptive Multichannel Combining and Equalization for Underwater Acoustic Communications, *J. Acoust. Soc. Amer.,* **94**(3): pt. 1. pp. 1621-1631, Sept. 1993.

[6] **Stojanovic, M. et al.,** Phase-coherent digital communications for underwater acoustic channels. *IEEE Journal of Oceanic Engineering*, **19**(1): p. 100-111, 1994.

[7] **Stojanovic, M., J. Catipovic, and J. Proakis,** Reduced-Complexity Multichannel Processing of Underwater Acoustic Communications Signals, *J. Acoust. Soc. Amer.*, **98**(2): pt. 1. pp. 961-972, Aug. 1995.

[8] **Freitag, L., J. Catipovic and R. Eastwood**, Acoustic Communications System for the AMMT Program, *Proc. Oceans 96*, Ft. Lauderdale, Sept. 1996.

[9] **Johnson, M., L. Freitag and M. Stojanovic**, Improved Doppler Tracking and Correction for Underwater Acoustic Communications, *Proc. ICASSP 97*, Munich, April 1997.

[10] **Freitag, et. al,** A Bidirectional Coherent Acoustic Communication System for Underwater Vehicles, *Proc. Oceans 98*, Nice, France, 1998.

[11] **Nagle, D., J. Edelson, L. Freitag and J. Catipovic**, High–data-rate Tactical Acoustic Communications Results Between Submarines, Surface Vessels, and UUVs (U)," U. S. Navy J. of Underwater Acoustics, **50**(4), pp. 943-959, Oct. 2000.

[12] **Nagle, D., J. Edelson and L. Freitag**, Medium-Frequency Tactical Acoustic Communication System Design and Performance (U), U. S. Navy Journal of Underwater Acoustics, **50**(4): pp. 961-987, Oct. 2000.

[13] **Stojanovic, M. and Z. Zvonar**, Multichannel Processing of Broad-Band Multiuser Communication Signals in Shallow Water Acoustic Channels. *IEEE Journal of Oceanic Engineering*, **21**(2): p. 156-166, 1996.

[14] **Stojanovic, M. and L. Freitag**, Multiuser Undersea Acoustic Communications in the Presence of Multipath Propagation, *Proc. Oceans 2001*, Hawaii, pp. 2165-2169, 2001.

[15] **Stojanovic, M., L. Freitag, and M. Johnson,** Channel-Estimation-Based Adaptive Equalization of Underwater Acoustic Signals, *Proc. Oceans 99*, Washington, 1999.

[16] **Rouseff, D, et. al.,** Underwater Acoustic Communications by Passive Phase Conjugation: Theory and Experimental Results, *IEEE Journal of Oceanic Engineering*, **26**, pp.821-831, 2001.

[17] **Preisig, J.**, Coherent Acoustic Communications through the Imperfect Ocean: Adaptive Least Squares, Time Reversal, and Connections to Adaptive Array Processing, *2003 IEEE Underwater Acoustic Signal Proc. Workshop*. W. Greenwich, RI, Oct., 2003.

[18] **Preisig, J.**, The impact of Underwater Acoustic Channel Structure and Dynamics on the Performance of Adaptive Coherent Equalizers, at *High Frequency Ocean Acoustics Conference* 2004. La Jolla, CA, March, 2004.

[19] **Preisig, J.**, Adaptive Channel Equalization in the Time-Varying Underwater Acoustic Channel: Performance Characterization and Robust Equalizers, at *12th Annual Workshop on Adaptive Sensor Array Processing*, Lexington, MA, March 16 - 18, 2004.

[20] **Stojanovic, M., J. Proakis and J.Catipovic**, Analysis of the Impact of Channel Estimation Errors on the Performance of a Decision Feedback Equalizer in Multipath Fading Channels, *IEEE Tr. on Comm.*, **43**(2/3/4): pp.887-886, 1995.

[21] **Nadakuditi, R., and J. Preisig**, A channel subspace post-filtering approach to adaptive least-squares estimation and equalization. To appear in *IEEE Tr. on Signal Proc.*

[22] **Ebert, P.M.,** *Error Bounds for Parallel Communication Channels*, Massachusetts Institute of Technology: Cambridge, MA, 1966.

[23] **Rayleigh, G. G. and J. M. Cioffi,** Spatio-Temporal Coding for Wireless Communication. *IEEE Trans. on Communication*, **46**(3): p. 357-366, 1988.

[24] **Kilfoyle, D. J. Preisig, and A. Baggeroer**, Spatial Modulation over Partially Coherent Multiple-Input / Multiple-Output Channels. *IEEE Transactions on Signal Processing*, **51**(3): p. 794-804, 2003.

[25] **Kilfoyle, D. and L. Freitag**, Spatial Modulation in the Underwater Acoustic Channel, *Proc. Array, Sensors, and Adaptive Proc. Workshop*, Lincoln Laboratories, Mar. 2004.