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Adaptive coding/modulation for shallow-water UWA communications

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We consider adaptive modulation and coding (AMC) techniques for Phase Shift Keying (PSK) transmission schemes in underwater acoustic (UWA) channels. To select a particular modulation and coding scheme at the transmitter, we examine the use of two channel quality indicators (CQIs) as adaptation metrics: achievable information rate with i.i.d. Gaussian inputs and post-equalization SNR. We explore the use of these adaptation metrics through simulation and using data recorded during the recent *AUVfest 2007* experiment. To evaluate AMC techniques for UWA communications, we have transmitted signals having a broad range of bit rates, obtained by varying the number of transmit elements, the modulation scheme, and the code rate. We present results demonstrating the feasibility of using our two channel quality indicators as adaptation metrics for choosing the modulation and coding scheme that achieves the highest rate supported by the available channel.

1 Introduction

Spectral efficiency is critical in the context of UWA communications, since the available bandwidth is severely limited by frequency dependent attenuation and significant transmission losses with distance. Time-varying, extended intersymbol interference (ISI) and relative motion between the transmitter and receiver produce both significant Doppler shifts and spreads which combine to limit high speed, phase coherent communications over UWA channels. Ref. [1] proposed a receiver structure which enabled phase coherent, single-input, single-output (SISO) communications over UWA channels. Ref. [2] extended the ideas presented in [1] to multi-input multi-output (MIMO) systems, space-time trellis codes (STTC), layered space-time codes (LSTC), low complexity adaptive equalizer structures and iterative processing at the receiver. Using a comprehensive set of data recorded in a shallow water channel with significant multipath, Ref. [2] demonstrated data rates and spectral efficiencies that single transmitter systems have not been able to match.

This paper focuses on adaptive modulation and coding (AMC) techniques for existing high-rate, phase-coherent, UWA communication systems in order to maximize the bit rates. There has been much research on AMC techniques for terrestrial wireless channels. Adaptive modulation for frequency selective fading channels has been studied in [3–5], where pseudo-SNR or post-equalization SNR is used as a channel metric for adaptation. AMC techniques for the UWA communications scenario have been considered in [7, 8]. Ref. [6] presents an adaptive modulation scheme for MIMO systems which uses coded QAM signaling schemes over fading channels. Ref. [7] describes a UWA communication system which adapts transmit power on a packet-by-packet basis. Ref. [8] proposes a robust adaptive UWA communication system which switches between coded M-FSK and phase coherent modulation (PSK and QAM), both using a convolutional code. The channel metrics used for adaptation are the multi-path delay spread, Doppler spread and the SNR, which are estimated with the help of a wideband probe used at the beginning of each data packet. The transmission parameters that are adapted include modulation, coding, and symbol rate.

In this paper, we propose a variable-rate AMC technique for UWA communications that varies the modulation or constellation size and the code rate, to provide a variety of transmitted bit rates. The schemes we consider are turbo coded PSK transmissions proposed in [2]. We use a receiver structure consisting of a decision feedback equalizer (DFE) with an embedded phase locked loop (PLL), followed by an iterative decoder (employing MAP decoders for component codes), with the possible exchange of soft information between the equalizer and the MAP decoders to facilitate turbo equalization [2]. To select the highest rate that the channel will support, we propose to use two channel quality indicators (CQIs) as adaptation metrics, *Achievable Information Rate with i.i.d. complex Gaussian inputs* and *Post-Equalization SNR*. We assert that these parameters are accurate indicators of the state of a frequency selective fading channel such as the UWA channel. We also describe the extension of our proposed AMC scheme to MIMO systems over UWA channels.

In order to examine the feasibility and effectiveness of our proposed AMC algorithm, we present experimental results obtained by decoding real data from a shallow water channel recorded during the *AUVfest 2007* experiment, and simulated data produced by a UWA channel simulator. We will present results indicating that information rate with i.i.d. Gaussian inputs and post-equalization SNR are effective CQIs for a practical AMC scheme in phase coherent UWA communications.

The paper is organized as follows. Section 2 reviews the turbo coded PSK transmission schemes under consideration in the paper. Section 3 describes the receiver structure employed, that was originally proposed in [2]. Section 4 discusses the AMC technique for UWA communications that is proposed in the paper. Section 5 presents an illustration of the proposed technique for MIMO and SISO systems via experimental and simulation results. Section 6 makes some concluding remarks.

2 Turbo Coded PSK Schemes

We consider turbo coded PSK transmissions originally proposed for UWA channels in [2,9] for our proposed implementation of AMC for UWA communications. This involves spatially multiplexing the input bit stream across the transmit elements to constitute several independent sub-streams. Each of these sub-streams is encoded using a turbo code, passed through a channel interleaver, and mapped into PSK modulation symbols before being transmitted over the UWA channel. Since independent streams are transmitted using each transmit element, the spectral efficiency of the system increases linearly with the number of transmit elements.

3 Receiver Structure

Refs. [2,9] describe the MIMO receiver structure and algorithm we will use with turbo coded PSK transmission schemes. This consists of a MIMO DFE with an embedded digital PLL driven by a combination of the RLS algorithm for the equalizer tap updates and a second order update equation for the carrier phase estimate. The use of the successive interference cancelation (SIC) DFE is also incorporated, which carries out equalization with channel estimation and ordered successive interference cancelation.

The channel impulse response (CIR) vector is estimated using an approximation to the RLS algorithm; the estimation technique is detailed in [2]. The MIMO DFE is followed by a MAP decoder, which operates on the equalizer output to yield an estimate of the original information bit sequence. It is also possible to lower the BER of the system further by exchanging soft information between the equalizer and the MAP decoder in an iterative fashion, i.e., by performing iterative (turbo) equalization [10]. Refs. [2, 9] describe the iterative DFE structure and turbo equalization in the context of MIMO UWA systems.

4 AMC for UWA Communications

The basic AMC technique that we propose for the UWA scenario is a *Variable Rate* technique. Variable rate techniques vary the modulation type (constellation size), the code rate, and possibly, in the context of MIMO transmissions, the number of transmit elements, to produce different transmission rates. The modulation and coding scheme we use is turbo coded PSK: the message bits to be transmitted are turbo-encoded and modulated using BPSK, QPSK or 8-PSK before being transmitted. Our AMC technique identifies the constellation and rate that best take advantage of the available channel, using the time-evolving CQIs, which should accurately represent the state of the channel.

We propose to use *achievable information rate with i.i.d. Gaussian inputs* and *Post-Equalization SNR* as CQIs to represent the state of a frequency selective fading channel (such as a UWA channel). The basic idea is to estimate one or both of the afore-mentioned CQIs at the receiver and to tune the signal transmission parameters (modulation scheme / code rate) to provide the highest bit rate that the channel will bear. A practical implementation would partition the CQI values into mutually exclusive intervals and assign transmission modes (consisting of specific combinations of the above-mentioned transmission parameters) to each interval. Each transmit mode will have a threshold value for the CQI being employed for activation (i.e. delimiting its activation interval from below). The CQI thresholds and the corresponding transmission modes that are activated must be picked to maximize the spectral efficiency for a given channel condition and provide adequate bit error rates for the given application. The computation of the above-mentioned CQIs could be facilitated by the insertion of pilot symbols at the beginning of each transmission frame.

The use of pilot symbols for channel estimation and to aid modulation and detection for fading channels has previously been explored in [12, 13]. Either or both of our proposed CQIs could be estimated from a set of training symbols at the beginning of the data frame and used to select the optimal transmit scheme for the return packet. In our proposed AMC scheme, this will consist of a specific modulation scheme and a turbo code rate. This selected mode is then maintained throughout the transmission of the data frame. The performance of such an adaptive modulation scheme will, of course, depend on factors such as feedback delay, errors introduced by the feedback channel and rapidity of the channel fading. However, we can expect performance gains in the form of spectral efficiency and system robustness under reasonable assumptions on the afore-mentioned limiting factors.

The proposed AMC technique can be extended to the case of MIMO UWA systems as well. Ref. [14] derives the capacity of a discrete-time Gaussian ISI channel having a real-valued impulse response with AWGN. Ref. [15] extends this technique to address the more general case of MIMO systems with complex CIRs and AWGN. We use the results in [15] to compute the achievable information rate with i.i.d. Gaussian inputs, one of the proposed CQIs for our AMC technique. From [15], the achievable information rate with i.i.d. Gaussian inputs is found to depend on (i) The SNR at each receive element and (ii) The CIR for each transmit/receive link.

Another metric that can be used is the post-equalization SNR (PES) computed at the output of the DFE. Assume that the estimation error at the equalizer output is $e_i(n)$. Then, the post-equalization SNR is defined as:

$$\gamma_{dfe} = \frac{E|d_i(n)|^2}{E|e_i(n)|^2} = \frac{1}{E|e_i(n)|^2},$$

where $d_i(n)$ is assumed to be known during training and is replaced by the hard symbol estimate $\tilde{d_i}(n)$ during the decision directed mode. The above equation assumes, of course, that the concerned signal constellation points have unit energy, i.e., $E|d_i(n)|^2 = 1$. Therefore, the post-equalization SNR may be computed by taking the sample mean of the energy of the error sequence $e_i(n)$. As mentioned earlier, the computation of this metric may be carried out by equalizing a small block of pilot symbols at the start of each data frame.

5 Experimental/Simulation Results

In this section, we present some decoding results from the *AUVfest 2007* UWA communications experiment, as well as simulation results generated with the aid of a UWA channel simulator. Decoding results are shown for data frames corresponding to various attempted transmission rates, along with computed values of our proposed CQIs.

5.1 Experimental Setup and Transmission Schemes

The *AUVfest 2007* experiment was conducted in the Gulf of Mexico in June 2007. A 10-element transmit array (of which eight transmitters were used during the test) was deployed from one small boat and an 8-element receive array was deployed from another small boat at ranges of 500 m to 3500 m in steps of 500 m. The water column was roughly 20 m deep and the bottom composition was sandy, and from looking at the channel measurements, very absorbing. The ocean surface roughness varied with the wind conditions, with wave heights up to 2 meters. The transmissions were organized into packets, each packet consisting of a series of up and down LFM frequency sweeps (for synchronization), followed by a packet using a particular modulation and coding scheme. A wide variety of modulation and coding schemes were transmitted, so that we could demonstrate AMC in post-processing. For testing our proposed AMC schemes, we process the data at the 500 m range, since the channel ISI is the worst at this range.

The transmissions are carried out over a bandwidth of $\sim$ 15 kHz (25.5 $-$ 40 kHz): the transmitted data sets involve splitting the available overall bandwidth into smaller sub-bands, each of bandwidth 2.5 kHz, in order to reduce the effective duration of ISI (as measured in symbol periods). The carrier frequencies employed in this multi-band transmission scheme are 26.75, 29.75, 32.75, 35.75 and 38.75 kHz. A guard band of 0.5 kHz is employed between adjacent frequency bands. A root raised cosine pulse is used to shape the power spectral density.

Different transmission rates are produced by varying the modulation scheme (BPSK / QPSK / 8-PSK), turbo code rate (1/3, 1/2, 2/3, 3/4, 7/8), and the number of transmit elements. For the BPSK case, turbo code rates 1/3, 1/2, 2/3 and 3/4 are attempted. The receiver array has a total of eight receive elements for all the transmissions. The specific turbo code employed is a $[1, \frac{5}{7}]$ code: varying code rates are achieved with different puncturing mechanisms. The interleaver lengths used for the various turbo code rates are: 3200 for code rate $R_c = 1/3$, 4800 for $R_c = 1/2$, 6400 for $R_c = 2/3$ and 7200 for $R_c = 3/4$. For the QPSK case, turbo code rates 1/2, 2/3, 3/4 and 7/8 are attempted. The interleaver length corresponding to code rate $R_c = 7/8$ is 8400.

The SNR is one of the inputs to the previously described achievable information rate computation algorithm, along with the CIR. For the real data scenario, the SNR is computed by estimating the signal and noise powers: this is facilitated by taking the sample mean of the discrete received sequence and using the silence periods that are inserted for synchronization purposes, to estimate the noise variance. In order to estimate the CIR, we employ the channel estimation technique described in [2], which is a variant of the RLS algorithm.

The PES is computed at the output of the equalizer as described earlier. In the MIMO case, we initially compute the mean squared error (MSE) at the output of the MIMO DFE for each transmit element. The error rate criterion for activating a certain mode of transmission is that the information bits corresponding to all the n_T data streams should be recovered without any errors, where n_T is the number of transmit elements. Therefore, we pick the largest MSE value and use it to compute the PES, which then constitutes the corresponding CQI value.

5.2 Experimental Results for the SISO System

The *AUVfest 2007* experiment did not incorporate a true AMC system with feedback and rate adaptation at the transmitter; it involved back-to-back transmission of a bank of signals with varying constellation sizes, code rates, and numbers of transmit elements. For the various attempted transmission rates, data frames transmitted along each of the carrier frequencies are decoded, and the corresponding CQI metrics evaluated: this is useful in examining the feasibility of the proposed AMC technique for UWA communications. Since each of the decoded sub-bands is impacted by a different multi-path structure, a dual purpose is served in our scenario: (i) The relevance of the proposed CQIs may be established by studying the error rates returned by the receiver at various sub-bands and the corresponding estimated values of the CQIs; and (ii) The variation in receiver performance from one sub-band to another in terms of the error rates obtained could be used to establish the CQI thresholds for each transmission mode (modulation scheme / code rate). To accomplish these objectives, a detailed study of multiple data frame decoding results and corresponding CQI metric values was carried out in [17], for the various code rates attempted with BPSK and QPSK. In this section, however, we show results only for the QPSK, $R_c = 1/2$ case for illustrative purposes, and present a summary of the results arrived at in [17].

Let us consider, then, the QPSK SISO transmission with a turbo code of rate $R_c = 1/2$. Table 1 shows the decoding results obtained for the various channel realizations or bands, along with the computed values of the achievable information rate with i.i.d. Gaussian inputs and post-equalization SNR. The number of MAP decoder iterations employed is 12; a maximum of 3 turbo equalization iterations are employed. From Table 1, we observe that only the band centered at 26.75 kHz is decoded without errors; the multiple numbers in the bit errors row of the table refer to multiple iterative equalizer passes. Therefore, the PES and achievable information rate corresponding to this band (symbol errors: 854/4800), i.e., 5.48 dB and 6.94, may be heuristically fixed as threshold values of the above CQIs for which the receiver in concern decodes a QPSK, $R_c = 1/2$ data frame (a spectral efficiency of 1 bps/Hz), without any errors.

A similar exercise is carried out in [17] for all the other turbo code rates attempted with BPSK and QPSK as well; we summarize the resultant thresholds obtained in Table 2. Decoding results and CQI values corresponding to all five sub-bands are examined in [17]; for each combination of modulation scheme and code rate, the validity of the proposed thresholds is affirmed by considering another transmission of the same data frame over a different transmission range, and examining the decoding results obtained, along with the corresponding CQI values. The associated analysis clearly illustrates the significance of the achievable information rate and PES as accurate indices of the channel quality and the receiver performance for a given channel condition.

5.3 Experimental Results for the MIMO System

In this section, we consider decoding results for the MIMO transmission case. Decoding results are shown for data frames corresponding to the QPSK, $R_c = 1/2$ transmission. $(n_T, n_R) = (2, 3)$, where n_T is the number

f_c **(kHz)**	**26.75**	**29.75**	**32.75**	**35.75**
Sym Err (/4800)	854	2268	1917	1409
Bit Err (/4800)	0	1588,1590, 1540	1401,1364, 1358	996,924, 874
P.E.S. (dB)	5.48	2.33	3.94	5.13
Inf. Rate	6.94	6.45	6.74	6.86

Table 1: Decoding results with computed CQI values for QPSK SISO Transmission with $R_c = 1/2$. $(06 - 11 - 2007$; Range: 500m). ('Sym Err' is the number of symbol errors; 'P.E.S' refers to post-equalization SNR).

Modulation	**Code Rate** (R_c)	**P.E.S. (dB)**	**Ach. Inf. Rate**
BPSK	1/3	2.16	6.05
BPSK	1/2	2.93	6.42
BPSK	2/3	4.26	6.52
BPSK	3/4	4.48	6.61
QPSK	1/2	5.48	6.94
QPSK	2/3	7.29	7.20
QPSK	3/4	7.67	7.47
QPSK	7/8	8.02	7.65

Table 2: Summary of CQI threshold values for SISO turbo coded PSK transmission schemes (P.E.S refers to post-equalization SNR).

of transmit elements, and n_R is the number of receive elements. Table 3 shows the decoding results obtained: we note that the threshold CQI values that yield zero bit errors for both data streams for the $(n_T, n_R) = (2, 3)$ QPSK MIMO transmission with $R_c = 1/2$ (a spectral efficiency of 2 bps/Hz) are: PES = 6.26 dB and achievable information rate = 12.59. The observation is that the PES threshold in this scenario is presumably tied to transmitter 1, since that is the data stream that is challenging the decoder for this scenario, more than the data stream from transmitter 2. The achievable information rate with i.i.d. Gaussian inputs will mirror the possibly poor state of the channels as seen from transmitter 1 as well, but in a less obvious manner.

For the same $(n_T, n_R) = (2, 3)$ MIMO system, it is found, from similar decoding results, that the thresholds for the BPSK, $R_c = 1/3$ case are: PES = 4.21 dB, and achievable information rate = 11.27; the thresholds for the BPSK, $R_c = 1/2$ case are found to be: PES = 4.5 dB, and achievable information rate = 11.71. Due to lack of error rate resolution, exact adaptation thresholds have not been determined for the BPSK, $R_c = 2/3$ and $R_c = 3/4$ cases: the PES thresholds presumably lie between 4.5 and 6.26 dB, and the information rate thresholds lie between 11.71 and 12.59. The QPSK rates 2/3, 3/4, and 7/8 data frames were not successfully decoded with only three receive elements: the adaptation thresholds for these rates will be higher than those arrived at for the QPSK $R_c = 1/2$ case.

f_c **(kHz)**	**26.75**	**29.75**	**32.75**
Sym Err Tx 1 (/4800)	1090	2077	1992
Bit Err Tx 1 (/4800)	552,90, 0	1500,1493, 1509	1443,1360, 1339
Sym Err Tx 2 (/4800)	202	958	2237
Bit Err Tx 2 (/4800)	0	248,0	1646,1636, 1683
P.E.S (dB)	6.26	4.39	4.95
Inf. Rate	12.59	10.94	10.88

Table 3: Decoding results with computed CQI values for QPSK MIMO Transmission with $R_c = 1/2$. $(n_T, n_R) = (2, 3)$. $(06 - 11 - 2007$; Range: 1500m).

5.4 Simulation Results for the MIMO Transmission Case

We now present decoding results and demonstrate how our CQIs can be partitioned to form an AMC scheme using data produced by a UWA channel simulator called Virtex described in [16]. This channel simulator uses the Bellhop Gaussian beam propagation model to model the channel in a series of frames that follow both receiver and source motion and the motion of the ocean surface. After producing a series of "frozen ocean" frames at a sample rate sufficient to capture these motions, the received waveforms are calculated at the bandpass sample rate by interpolating the multipath arrival pattern between frames. This produces an extremely high-fidelity simulation of the dynamic channel effects likely to be encountered in a real ocean channel. A 2D dynamic ocean surface is synthesized by calculating the Pierson-Moskowitz spectrum for a particular wind speed and then using a dispersion relation to propagate a time-evolving realization of this spectrum in the direction of the wind. The case studies that are presented in this section were synthesized using a seafloor composed of clay and a wave height of 5 m.

Table 4 shows decoding results and corresponding CQI values for a BPSK MIMO transmission with turbo code rate $R_c = 1/3$ and $(n_T, n_R) = (2, 4)$. The *Ch 1, Ch 2,* etc. labels refer to various channel realizations obtained by considering multiple combinations of the frequency band that is decoded and the received SNR (or equivalently, noise level). From Table 4, we note that the threshold CQI values that yield zero bit errors for both data streams for the BPSK MIMO transmission with $R_c = 1/3$ (a spectral efficiency of 2/3 bps/Hz) are: PES = 2.26 dB and achievable information rate = 10.33. Similar decoding results yield a PES threshold of 3.18 dB, and an achievable information rate threshold of 13.45, for the BPSK MIMO transmission with $R_c = 1/2$ (a spectral efficiency of 1 bps/Hz). The threshold values put forth are higher than those for the $R_c = 1/3$ case: this is along expected lines and is in sync with the observations and conclusions that have been drawn thus far.

Realization	**Ch 1**	**Ch 2**	**Ch 3**	**Ch 4**
Symbol Errors Tx 1 (/9600)	1603	1542	1211	1133
Bit Errors Tx 1 (/3200)	363,2,0	350,174,0	0	0
Symbol Errors Tx 2 (/9600)	3	5	2	3
Bit Errors Tx 2 (/3200)	0	0	0	0
Post-Eq SNR (dB)	2.72	2.26	2.74	2.41
Ach. Inf. Rate	11.08	10.33	14.01	13.16

Table 4: Decoding results with computed CQI values for BPSK MIMO Transmission with $R_c = 1/3$. $(n_T, n_R) = (2, 4)$. (Simulated data: bottom surface: clay; wave height: 5 m).

6 Conclusions

In this paper, we have described a variable rate AMC technique for phase coherent UWA communication systems. The proposed AMC technique varies the modulation scheme and code rate at the transmitter. The turbo coded PSK transmission schemes under consideration were originally presented in [2, 9]. We have described how achievable information rate and post-equalization SNR can serve as as CQIs in both single and multiple transmitter systems. We have verified that these metrics accurately represent the state of the UWA channel and the error rate performance of the system in a given channel. We have demonstrated our proposed AMC technique through experimental results obtained by decoding data collected from the *AUVfest 2007* UWA communications experiment, as well as simulation results generated with the help of a UWA channel simulator.

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