Trellis Coded Modulation Schemes for Underwater Acoustic Communications

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Abstract — **Bandwidth efficient phase-coherent modulation techniques such as M-PSK have been made possible over underwater acoustic channels in recent years. It is well known that the error probability of the usual linear modulations such as M-PSK over fading channels varies inversely with the signal-to-noise ratio. To increase the slope of the error probability vs. signal-to-noise ratio curve, a diversity technique or an error correcting code may be used. The bandwidth limitations in the underwater channel being severe, we consider trellis-coded modulation for underwater acoustic communications and present simulation results performed to study their performance. Trellis-coded modulation offers a means of introducing diversity without paying in bandwidth.**

I. INTRODUCTION

An ever increasing number of underwater applications require tetherless Underwater Acoustic (UWA) communications to be possible. For many of these applications the communications has to be real-time requiring high data rates. The building of fast and reliable acoustic local area nets (ALANs) have also been proposed for facilitating the exchange of data, such as control, telemetry and video signals [1]. These ALANs could then be made compatible with the global internet making large amounts of data accessible to remote users. Signal degradations caused by multipath propagation and high temporal and spatial variability of the channel conditions pose many challenges to the design of digital communications systems over underwater acoustic (UWA) channels [2] [3]. However, if high data rates are to be achieved bandwidth-efficient phase-coherent modulation techniques such as phase shift keying (PSK) must be used [4]. Recent UWA communication system implementations using joint equalization and synchronization at the receiver have been able to achieve phase-coherent communications at high data rates [5]. Due to the high values of doppler spreads over the UWA channel, only at high data rates is it possible to achieve reliable coherent channel tracking [6]. But larger data rates imply more intersymbol interference. Coded modulation schemes therefore need to be considered for providing the necessary performance margins to make reliable high data rate communications feasible over the UWA channel.

We consider trellis-coded modulation (TCM) using coherent demodulation for UWA communications and present simulation results performed to study their performance. Diversity is often used to combat the effects of multipath and fading. TCM offers a means of introducing diversity without paying in bandwidth. Coded modulation using noncoherent demodulation and soft-decision decoding was described in [7] for the UWA channel. In [7] FSK modulation was combined with block coding. In [8] and [9] convolutional coding with sequential decoding with noncoherent demodulation was presented.

The organization of the paper is as follows. In Section II the UWA channel and the communication system model are presented. Section III the TCM schemes considered are discussed and in Section IV the simulation results of these TCM schemes over the shallow-water UWA channel model are presented. Finally, conclusions are given in Section V.

II. UWA COMMUNICATION SYSTEM MODEL

In several recent papers, for example [11] and [12], practical models of the UWA channel have been implemented to estimate performance. In [11] the fading is assumed to be Rayleigh and is characterized by multiplying the signal and its Hilbert transform by two Gaussian random variables with matched power spectra. A number of such fading paths, depending on the number of diffused paths from transmitter to receiver, are added to get the signal at the receiver. As the number of paths increases the performance improves as this model assumes that the signal paths add constructively and the channel tends towards a Ricean fading channel. In [12] the authors assume a direct signal and a diffuse multipath component and the concept is similar to that in [11]. Indeed for the shallow-water medium range channel the Rayleigh model seems best suited [2].

Unlike in the case of say the satellite mobile channel where test channels based on field measurements exist [10], in the case of the UWA channel no such configured channel models exist. Important figures of merit for a fading channel are the time dispersion, T_m, (experienced in terms of a channel delay spread and inter-

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[1] This work was partly supported by CSIR, India through a Research Grant (No:25(0086)/97/EMRI-II.)

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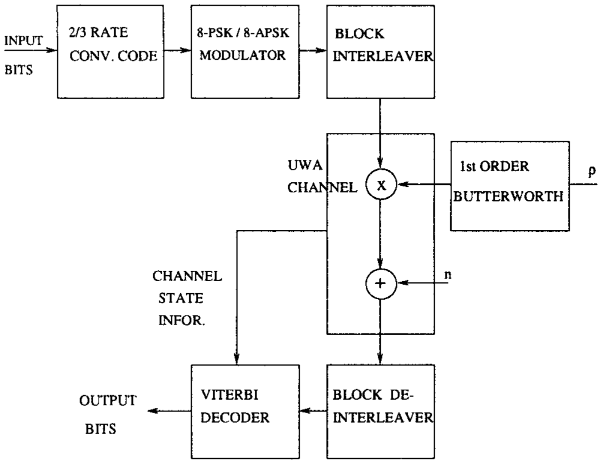


Fig. 1: System Model

symbol interference) and Doppler spreading, B_w, caused by time variations of the channel [13]. UWA channels suffer from extended multipath and phase instabilities. The multipath propagation causes intersymbol interference (ISI) extending to lengths of several symbol durations. High rate signalling causes many adjacent symbols to interfere. The receiver must be able to compensate for the ISI in order for phase-coherent signalling methods to be used. For the medium-range shallow water channel, a commonly encountered time dispersion value is 10 ms and Doppler Spreading is about 10 Hz. Considering a signalling rate of $1/T$ the normalized Doppler spread is given by $B_w T$. In [6] it is noted that the normalized Doppler spread, $B_w T$, has to be below 10^{-2} for reliable coherent channel tracking. Hence the signalling rate for the medium-range shallow water channel with $B_w = 10$ Hz has to be in excess of 1 KHz. At this signalling rate the ISI can extend to over 10 symbols and has to be effectively dealt with. For the vertical underwater channel time dispersion values can be very small making it possible for coherent channel tracking to take place without much decoding complexity as ISI is very small.

To establish coherent detection in the presence of strong multipath, a technique based on joint estimation of the carrier phase and the parameters of a decision-feedback equalizer for ISI compensation has been presented in [5]. The received signal after being brought to baseband and lowpass filtered, is frame synchronized using a known channel probe. The transmission is organized in such a way as to provide periodic frame synchronization and retraining for the equalizer. The carrier offset is corrected by the amount estimated in the process of joint equalization and synchronization. This method allows the coherent detection of modulation formats such as M-PSK or M-QAM.

A block diagram of a TCM scheme over the shallow-water UWA channel as considered by us is shown in fig. 1. Input bits are encoded by a trellis encoder to produce a coded 8-PSK symbol sequence of length N denoted by

$$\mathbf{X} = (x_1, x_2, \ldots, x_i, \ldots, x_N) \tag{1}$$

The receiver described above performs coherent detection and hence compensates the channel phase shift at the receiver. Therefore, the channel produces a noisy discrete-time sequence $\{y_i\}$ written as,

$$y_i = \rho_i x_i + n_i \tag{2}$$

at the receiver.

Here, $n_i = \text{Re}(n_i) + \text{Im}(n_i)$ is a complex noise process. $\text{Re}(n_i)$ and $\text{Im}(n_i)$ are uncorellated, zero mean Gaussian r.v.'s each with variance $\sigma^2 = N_o/2$. ρ_i is a random variable representing the random amplitude of the received signal. For a channel with only diffused multipath component the fading amplitude is Rayleigh distributed with a probability density function (pdf)

$$P_P(\rho) = 2\rho e^{-\rho^2} \tag{3}$$

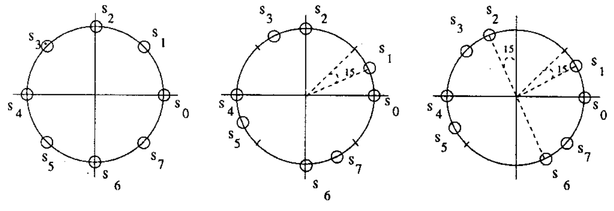
This pdf has been normalized, that is the fading amplitude, ρ has a mean-squared value of unity. This implies that the measured signal energy at the receiver represents the average signal energy per channel symbol, E_s. We assume that the fading amplitude, ρ, is perfectly estimated at the reciever, i.e. channel state information (CSI) is available. Interleaving is performed to reduce the effect of correlated fading among adjacent symbols.

The two sequences $\{y_i\}$ and $\{\rho_i\}$ are the inputs to the TCM decoder which performs maximum likelihood (ML) decoding.

To model the ISI we have used a third order Butterworth filter of 3-dB bandwidth 0.01 (the normalized doppler spread). As mentioned above interleaving is used to combat correlated fading. The Viterbi algorithm assumes that the channel is memoryless and becomes non-optimal in the absence of interleaving. We use a block interleaver. It is modeled as a buffer with d rows (depth of interleaving) and s columns (span of interleaving). The size of the interleaver in symbols is, therefore, $d \times s$. At the transmitter data is written into the buffer in successive rows and read out in columns into the channel. At the receiver the deinterleaver performs the reverse operation.

III. TCM SCHEMES FOR UWA CHANNEL

TCM enhances the reliability of the communication system without paying in bandwidth or power. This is achieved by expanding the signal set to compensate for the redundancy due to coding [14]. Using a rate $n/n+1$ convolutional code the encoder maps n bits to one of 2^{n+1} PSK waveforms. Hence, the data transmission rate (and bandwidth) remain the same for the coded case and the uncoded case.



(a) (b) (c)

Fig. 2: (a) Symmetric 8-PSK (b) Asymmetric 8-PSK signal set for 4-state TCM (c) Asymmetric 8-PSK signal set for 8-state TCM

As described above we have assumed the shallow-water medium range UWA channel to be Rayleigh fading. It is known [15] that for large signal to noise ratios the error event probability of a TCM scheme in a Rayleigh fading channel with ideal coherent detection, with perfect channel state information and independent fading in each channel symbol, is asymptotically approximated as

$$P_e \approx \frac{\alpha(L, d_p^2(L))}{(\frac{1}{4N_o})^L d_p^2(L)} \tag{4}$$

where, L denotes the smallest effective length of the code, $d_p^2(L)$ denotes the maximum squared product distance between signal points of error event paths with effective length L and $\alpha(L, d_p^2(L))$ denotes the average number of code sequences having effective length L and squared product distance $d_p^2(L)$.

The code design criteria for Rayleigh fading channels with perfect CSI are,

1. maximize the smallest effective length of the code L, and
2. maximize the smallest product of the squared distances, $d_p^2(L)$, of signals along the error events of effective length L.

Following these rules many TCM schemes have been constructed for the Rayleigh fading channel [16]-[20]. We consider the best 4-state and 8-state rate 2/3 8-PSK TCM schemes, from [17] and [14] respectively and 4-state and 8-state rate 2/3 asymmetric 8-PSK (8-APSK) TCM schemes, from [19] and [20] respectively. The state transition matrices for the 4-state rate 2/3 8-PSK and 8-APSK codes is given in Table 1 and for the 8-state rate 2/3 8-PSK and 8-APSK codes is given in Table 2. For the symmetric 8-PSK codes the constellation used is given in Fig. 2(a). For the 4-state 8-APSK TCM scheme the signal set used is shown in Fig. 2(b) and for the 8-state 8-APSK TCM scheme the signal set used is shown in Fig. 2(c).

IV. SIMULATION RESULTS

The simulation results for the case of infinite inter-

State	S_0	S_1	S_2	S_3
S_0	s_0	s_4	s_2	s_6
S_1	s_3	s_7	s_1	s_5
S_2	s_6	s_2	s_4	s_0
S_3	s_5	s_1	s_7	s_3

Table 1: State transition matrix for 4-state TCM code [17].

State	S_0	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_0	s_0	s_4	s_2	s_6	x	x	x	x
S_1	x	x	x	x	s_1	s_5	s_3	s_7
S_2	s_4	s_0	s_6	s_2	x	x	x	x
S_3	x	x	x	x	s_5	s_1	s_7	s_3
S_4	s_2	s_6	s_0	s_4	x	x	x	x
S_5	x	x	x	x	s_3	s_7	s_1	s_5
S_6	s_6	s_2	s_4	s_0	x	x	x	x
S_7	x	x	x	x	s_7	s_3	s_5	s_1

Table 2: State transition matrix for 8-state TCM code [14]. (x denote invalid state transitions)

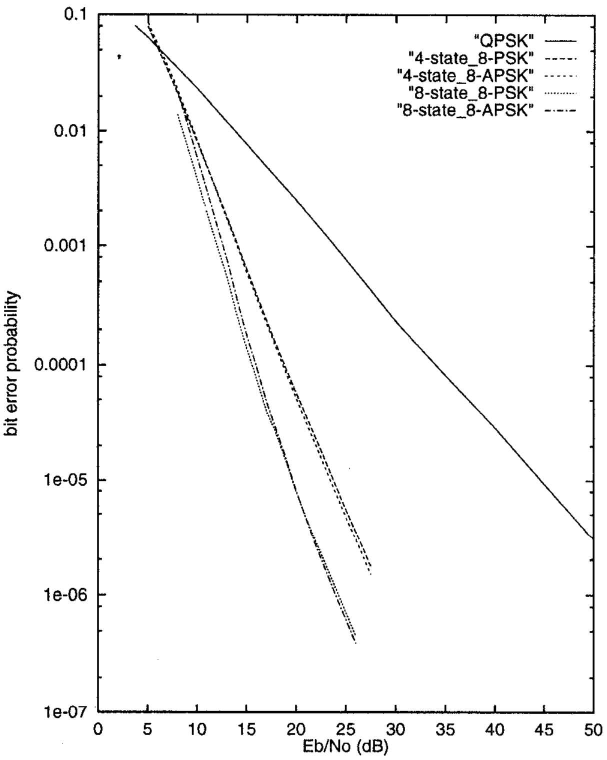


Fig. 3: Simulation results comparing QPSK with 4-state and 8-state 8-PSK and 8-APSK TCM schemes for fading channel with perfect CSI and infinite interleaving/deinterleaving

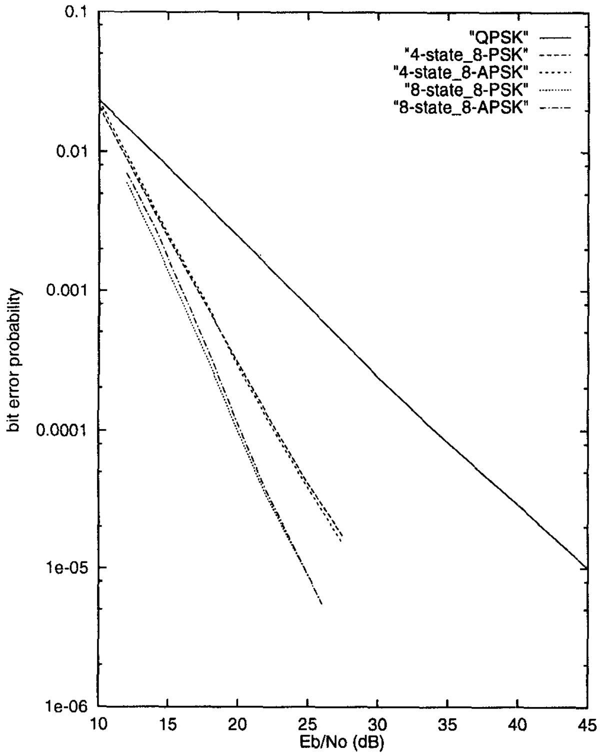


Fig. 4: Simulation results comparing QPSK with 4-state and 8-state 8-PSK and 8-APSK TCM schemes for fading channel with perfect CSI and finite interleaving/deinterleaving ($d = 16 \times s = 8$)

leaving/deinterleaving and a finite case are presented. The model presented in Section II has been used for the simulation. For the case of finite interleaving the size of the block interleaver used is $d = 16 \times s = 8$. The correlated random amplitudes of the channel are generated a first-order Butterworth filter of 3dB normalized bandwidth 0.01. Interleaving effectively increases the fading bandwidth. For simulating the infinite interleaving/deinterleaving case the random variable is not filtered. Hence subsequent samples remain uncorrelated.

Figures 3 and 4 show the results of our simulation for the infinite interleaving/deinterleaving and finite interleaving/deinterleaving cases respectively. It is noticed that the 8-APSK TCM schemes give a further 0.3-0.4 dB gain over 8-PSK TCM schemes in addition to the large gains over the uncoded 4-PSK case. For the finite interleaving/deinterleaving case the gain is around 12 dB for 4-state code and 15dB for 8-state code at 10^{-4}. It is noticed that with infinite interleaving/deinterleaving the gain is larger. Depending on the delays allowed for a particular application the interleaving depth should be chosen. A larger depth implies more gain but it also means more decoding delay.

V. CONCLUSIONS

The application of TCM to the vertical UWA channel and the shallow-water medium range channels are considered. For probability of bit errors around 10^{-3} symmetric 8-PSK TCM schemes are proposed and for much smaller bit error probabilities asymmetric 8-PSK TCM schemes that give an additional 0.4 dB gain are proposed (about 10% additional savings in power). The gains obtained over the uncoded case are obtained without paying in bandwidth, which is precious over the underwater channel. Any reduction in power is welcome over the underwater channel as many of the ocean floor transmitters and receivers are battery operated and changing of batteries is very cumbersome. Further, multi-carrier schemes may be implemented using the TCM schemes discussed here to reduce the complexity of the equalization used or to even completely exclude equalization. In the multi-carrier case larger time dispersions are an advantage. A large time dispersion means the coherence bandwidth is small thus affecting only a limited number of subcarriers at a time. Codewords that are spread across subcarriers will thus be more robust in this case. We leave this as a problem for further research.

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