A New State-Drop Fast Sequence Estimation for TCM

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***Abstract*— In this paper, we developed a new State-Drop Fast Sequence Estimation (SDFSE) strategy for Trellis Coded Modulation (TCM) schemes for transmission in the Intersymbol Interference (ISI) environment. For the decoding of TCM signals in the presence of Additive White Gaussian Noise (AWGN), Maximum Likelihood Sequence Estimation (MLSE) has been considered as the optimum solution [13,16,17,19]. However, for band-limited ISI channels in the presence of AWGN, the complexity of optimum MLSE increases as a function of the ISI channel memory length. This prohibits practical implementation of MLSE. Over the past decades, a spurious research took place in the development of reduced complexity suboptimum decoding strategies for TCM schemes. Reduced State Sequence Estimation (RSSE) is one such implementation which emphasizes on reduced computational complexity Likelihood sequence estimation by minimizing the ISI-code trellis states [23].**

We provide a new suboptimum decoding strategy, a reduced computational complexity SDFSE which takes the path metrics of soft output Viterbi algorithm as a measure to decide and compute the state transitions of only-best-survivor in the succeeding intervals. The SDFSE results in a reduced number of nodes expansions during Likelihood sequence estimation as compared to RSSE. A decision parameter in comparison with the accumulated path metric of the best survivor is tuned to provide variable complexity for the algorithm.

We evaluated the error performance of SDFSE through computer simulation for 4-state 16-QAM TCM scheme in the ISI environment. The results are compared with the error performance of RSSE, which we consider as conventional-RSSE (c-RSSE). It is found that computational complexity of SDFSE is less, and hence is faster than c-RSSE. The SDFSE provides an error performance close to c-RSSE, and is a function of the decision parameter of SDFSE strategy.

Keywords—**Variable-Complexity; SDFSE; decision parameter; c-RSSE**

I. Introduction

Over the past few decades digital communications has been growing with a furious pace especially in the field of satellite and computer communications. The fact that there is greater demand for efficient high rate digital links has spurred an active research in the development of coded modulation schemes. It is the pioneer work of Ungerboeck who invented Trellis Coded Modulation (TCM) schemes [16,17] which laid the foundation for the research and development of efficient coded modulation schemes [3,4,6,7,8,10,11,12,16,17]. TCM is an integrated modulation and coding approach that results in a gain of few decibels in signal-to-noise ratio for a constant transmission rate and bandwidth. Today, TCM has been used in many advanced communication applications accordingly there has been a boomed research in the development of efficient modulation and demodulation techniques.

We developed a new decoding strategy for TCM schemes, namely, State-Drop Fast Sequence Estimation (SDFSE), a variable-complexity reduced state fast decoding algorithm for TCM transmission over band-limited ISI channels. The SDFSE is an integrated approach which takes the path metrics of modified soft output Viterbi algorithm which perform Likelihood sequence estimation, as a measure for state-drop executions. The SDFSE reduces the number of states expanded as a function of a decision parameter of the algorithm. We evaluated the error performance of SDFSE for 4-state 16-QAM TCM scheme through computer simulation.

This paper is organized as follows: In Section 2, general structure of TCM encoder/modulator has been considered. The Ungerboeck's model for 4-state 16-QAM TCM scheme is given and the optimum MLSE for TCM scheme is explained. In section 3, a brief description of finite state machine model of band-limited ISI channel and the Reduced-State Sequence Estimation (RSSE) is given. In Section 4, the new suboptimum decoding proposed in this paper namely, SDFSE is explained. Computer simulation results and conclusions are given in section 5. Next Section contains the acknowledgement and then references are listed.

II. TCM Encoder/Modulator

General structure of TCM encoder/modulator is depicted in Fig 1. The scheme employs redundant nonbinary modulation in combination with a finite state encoder which governs the selection of modulation signals. The finite state encoder is the convolutional encoder of rate - $\tilde{m}/(\tilde{m}+1)$. When m -bits are to be transmitted per encoder/modulator operation, bits are encoded by the convolutional encoder. The encoded $(\tilde{m}+1)$ bits select one of the subsets of M-ary signal set where $M = 2^{\tilde{m}+1}$. Remaining $m-\tilde{m}$ uncoded bits are used to determine one of $2^{m-\tilde{m}}$ signals of a subset for transmission. Trellis coded bits of size 2^{m+1} are mapped into one of the symbols of M-ary constellation by the mapping function $g_1(x_n, \sigma_n)$ for transmission. The encoder can be described by a state transition (trellis) diagram. The trellis structure consists of $N_s = 2^{\nu}$ states where the constraint length of the encoder is ν. There are 2^m transitions from each state that corresponds to 2^m possible values of m-bit information. The trellis

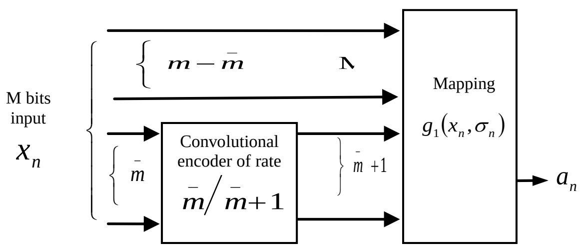

Figure 1. TCM encoder/modulator

branches are labeled with redundant nonbinary modulation signals [2]. The $\tilde{m}+1$ encoded bits of convolutional encoder divide the M -ary signal constellation into $2^{\tilde{m}+1}$ subset.

This corresponds to k^{th} level of set-partitioning of the signal constellation. Set-partitioning divides the signal set successively into smaller subsets with maximally increasing the smallest intra-set distances Δ_i i=0,1,2,… The partitioning is repeated $\tilde{m}+1$ times until the Euclidean distance $d_{\tilde{m}+k}$ is equal to or greater than the desired free distance of the TCM scheme to be designed. Each partition is two way. The labeling of partition tree by the $\tilde{m}+1$coded bits $z_n^{\tilde{m}+k},\ldots,z_n^0$ results in a label $\underline{z}_n$ for each subset. The label reflects the position of the subset in the tree. If the labels of two subsets agree in the last q position, but not in the bit $\underline{z}_n^q$, then the signals of the two subsets are the elements of the same subset at level q in the position tree. Thus they have Euclidean distance Δ_q .

In the structure of Ungerboeck's TCM encoder/modulator for 4-state 16-QAM scheme, the convolutional encoder is of rate - $\tilde{m}/(\tilde{m}+1)$. It accepts three input bits per symbol interval, given by

$$X_n = \{x_n^1, x_n^2, x_n^3\} \qquad (2.1)$$

One bit of information is fed to the convolutional encoder according to the rule $\tilde{m} \le m$, trellis encoded bits $\tilde{m}+1$ are represented by

$$Y_n = \{y_n^0, y_n^1, y_n^2, y_n^3\} \qquad (2.2)$$

The bits y_n^0 and y_n^1 select a subset of M -ary signal set and the bits y_n^2 and y_n^3 select one of the signals from the selected subset. The trellis structure for 4-state 16-QAM scheme has 4-states, two branches emerge from each state and each transition contains four parallel paths. Each transition represents one of the subsets of the 16-QAM signal constellation which is partitioned into 4-subsets.

A. *Maximum-Likelihood Sequence Estimation*

The optimum decoding strategy for TCM schemes in the presence of Additive White Gaussian Noise (AWGN) is the Maximum Likelihood Sequence Estimation (MLSE) implemented by soft output Viterbi Algorithm (SOVA). The MLSE traces the encoder trellis structure to find the shortest path in terms of the path metric for the next state transition. The trellis node can be represented with a pair (σ_n, n) where σ_n represents the state of the encoder at time n. The transition from the present state (σ_n, n) to the next state $(\sigma_{n+1}, n+1)$ is labeled with the branch metric which measures the likelihood that the encoder moves into state σ_{n+1} at time n+1.

The transmitted symbol a_n is given by

$$a_n = g_1(X_n, \sigma_n) \qquad (2.3)$$

where X_n is the information transmitted at the discrete time instant n. The state transition of the encoder is given by

$$\sigma_{n+1} = g_2(X_n, \sigma_n) \qquad (2.4)$$

During each symbol interval, the decoder identifies a node with the smallest accumulated metric and expands it. The SOVA expands all the nodes during each symbol interval T. It determines the transmitted sequence $\{\hat{a}_n\}$ which is closest in Euclidean distance to the noisy received sequence $\{z_n\}$ with respect to the node with the least accumulated metric.
Decoder input is defined as

$$z_n = a_n + w_n \qquad (2.5)$$

and $\{w_n\}$ is the AWGN noise samples with zero mean and variance $2\sigma_v^2$.

The path metric $M_n(a_n)$ computed by the SOVA at each of the trellis nodes is given by

$$M_n(..a_n) = M_{n-1}(..a_{n-1}) + |z_n - a_n|^2 \qquad (2.6)$$

III. BANDLIMITED ISI CHANNEL AND FSM

In a band-limited digital communication system, the effect of each symbol transmitted over a time-dispersive channel extends beyond the symbol interval [13,15]. Consequently, overlapping of received symbols occurs, which results in linear distortion called intersymbol interference (ISI). ISI turns out to be the primary obstacle to high speed data transmission over band-limited ISI channels. In a practical system, it is to assume that ISI affects a finite number of symbols [13,15,20], consequently, the cascade of a TCM encoder and the ISI channel can be viewed as a combined finite-state machine (FSM) and hence as a combined ISI-Code trellis called super-trellis whose states are given by the product of TCM encoder states and the ISI states. The receiver performs Maximum-Likelihood Sequence Estimation of the data sequence transmitted over band-limited ISI channel using SOVA that search for a minimum cost path in the super- trellis.

The FSM of a band-limited ISI channel corrupted by AWGN is shown in Fig. 2. The transmitted data symbol a_n is influenced by ISI and AWGN sample w (n).

Thus the received waveform is given by

$$r(n)=\sum_{i=0}^{L} p_i.a(n-i)+w(n) \qquad (3.1)$$

where { p_i } are the tap gains correspond to the sampled channel impulse response of the band-limited ISI channel.

The noise and the data sequences are assumed to be uncorrelated and the number of taps are (L+1) where L represents the channel memory length. If the signal constellation used for the transmission of $\{a(i)\}$ has an alphabet size of M symbols then the discrete-time channel can be represented by M^L-state trellis diagram. The combined ISI-code trellis state is given by

$$\mu_n=(a_{n-L},a_{n-L+1},...,a_{n-1};\sigma_n) \qquad (3.2)$$

where the symbol sequence $(a_{n-L},a_{n-L+1},..,a_{n-1})$ in the above expression correspond to a path which takes the TCM encoder from a previous state σ_{n-1} to the present state σ_n in compliance with the TCM coding rule. Correspondingly state transition of the FSM can be written as

$$\mu_n : a_n \rightarrow \mu_{n+1} \qquad (3.3)$$

The optimum decoder determines the sequence $\{\hat{a}_n\}$ which is closest to the received sequence given by

$$\{r_n\}=\{a_n+u_n+w_n\} \qquad (3.4)$$

and minimizes the path metric $M_n(..a_n)$ accordingly, which takes into account ISI due to past symbols $\{a_{n-i}\}$, given by

$$M_n(..a_n)=M_{n-1}(..a_{n-1})+\left|r_n-\sum_{i=1}^{L} p_{n-i}a_{n-i} - a_n\right|^2 \qquad (3.5)$$

A. Reduced State Sequence Estimation

Implementation of MLSE becomes prohibitively complex for band-limited ISI channels as the computation and storage requirement of the decoder grow exponentially with the channel memory length L as well as the encoder states. One approach to reduce the computational complexity of MLSE and the storage requirement is the Reduced State sequence Estimation technique [22,23]. By truncating the channel memory length to $J \le L$ ISI symbols reduces the complexity of combined ISI-code trellis structure and the computational complexity of conventional MLSE. Truncating the channel memory to J, for $0 \le J \le L$, the state complexity of the receiver is given $N_s(M/2^J)$. For each data symbol a_{n-i} transmitted, within the span of the truncated memory length J, the $\tilde{m}+1$ bit label characterizes the depth of set-partitioning, and determines the subset to which the symbol a_{n-i} belongs. Given the encoder states σ_n at time n, and the label sequence

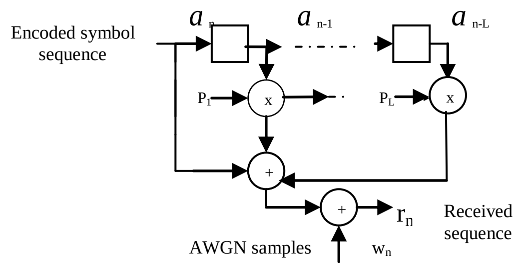

Figure 2. FSM of bandlimited ISI channel

$\{Y_{n-1}(m-1),Y_{n-2}(m_2)...,Y_{n-J}(m_J)\}$ the encode state μ_{n-k} at time n can be uniquely determined if $\tilde{m} \le m_i \le m$ for $i \le J$. The reduced states of the truncated code trellis is given by

$$\mu_n^k=\left[\sigma_n;Y_{n-1}(m_1),Y_{n-2}(m_2),...,Y_{n-J}(m_J)\right] \qquad (3.6)$$

Under the conditions $m \ge m_1 \ge m_2 \ge ... \ge m_J \ge \tilde{m}$ the reduced state structure leads to a family of structures, in each case, each code state is associated with $2^{m_1+m_2+...+m_J}$ number of states. For each of the reduced states 2^{m_1} transition group originate with each group consisting of 2^{m-m_1} parallel transitions. Each state carries information about subsets rather than the data symbols. The performance degradation due to $L-J$ ISI terms not represented by the truncated combined state μ_n^J is compensated by incorporating an ISI-cancellation mechanism into the branch metric computation. Each truncated combined state μ_n^J gives information on J past symbols $\{a_{n-i}\}$, for $1 \le i \le J$ associated with that state. Associated with state μ_n^J there will be a unique survivor path with a history of path symbol estimates and a survivor path metric defined by

$$M_n(..a_n)=M_{n-1}(..a_{n-1})+\left|z_n - \sum_{i=J+1}^{L} p_{n-i}\hat{a}_{n-i} - \sum_{i=1}^{J} p_i a_{n-i} - a_n\right|^2 \qquad (3.7)$$

The simplest among RSSE techniques is the Parallel Decision Feedback Decoding (PDFD) for which $J=0$ and the decoder trellis structure is same as the encoder trellis. As the complexity increases RSSE approaches the performance of MLSE [22,23].

IV. State Drop Fast Sequence Estimation

The MLSE implemented using soft output VA and the c-RSSE implemented using modified soft output Viterbi algorithm expands all the nodes of the trellis being traced. The new SDFSE is a variable Complexity suboptimum decoding strategy for TCM schemes in the ISI environment. We emphasize on reducing the computational complexity of c-RSSE through SDFSE. The SDFSE is an integrated approach for Likelihood sequence estimation of TCM signals corrupted by the channel ISI and AWGN, with tunable computational complexity.

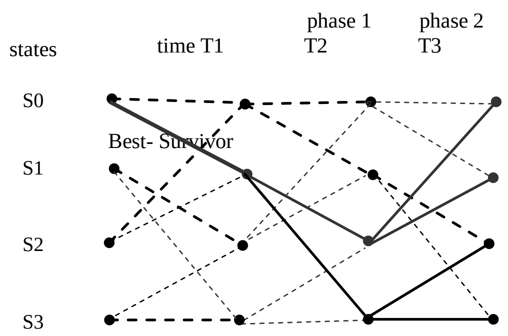

Figure 3. State expansion in SDFSE for 4-state 16-QAM TCM scheme

During each symbol interval T, SDFSE expands only-best-survivor node of the trellis whenever tentative decision during T-1 interval reflects near optimum condition. The decision parameter of the SDFSE algorithm is used to predict whether to expand only-best-survivor node or all the nodes of the combined ISI-code trellis in the succeeding intervals. Whenever the SDFSE algorithm enters state-drop mode, it will resume all the states after all the phases of state-drop mode is completed. The SDFSE strategy reduces the computational complexity of the decoder by reducing the number of nodes expanded. The decision parameter is used to predict the only-best-survivor node expansion which provides a tunable complexity for the algorithm. The technique does not require additional storage and, the only overhead introduced is the decision parameter estimation. The Fig 3 depicts state transitions for SDFSE. The least complexity c-RSSE trellis structure of 4-state 16-QAM TCM scheme is used. For the 4-state 16-QAM TCM scheme, the only-best-survivor node expansion takes two phases which require reduced computations than c-RSSE. The error performance of SDFSE has been evaluated for 4-state 16-QAM TCM scheme and various ISI channels simulated are listed in Table. I. The simplest case of c-RSSE that is Parallel Decision Feedback Decoding (PDFD) has been simulated for error performance comparison.

V. Results and Conclusions

The SDFSE performance is evaluated for 4-state 16-QAM TCM scheme in the ISI environment in the presence of AWGN. Table I give the list of ISI channels simulated. The channels memory length is assumed as 1, and, in each case the results are compared with the error performance characteristics obtained for c-PDFD technique. Error performance of uncoded 8-QAM scheme is also evaluated using c-PDFD in the presence of ISI and AWGN for comparison.

In Fig. 4 error performance characteristics are given for the ISI channel CH11 of Table I, and the decision parameter is x1. The curve No.2 from right represents the error event probability Vs SNR characteristic for the SDFSE strategy. The curve No.3 represents the error event probability Vs SNR for the c-PDFD strategy and the curve 4 shows the error performance for ISI free condition. It is observed that SDFSE performance is close to that of c-PDFD performance with a small amount of performance degradation of about 0.2 db at high SNR, due to the suboptimal approach, at an error event probability rate of 10^{-4}. Table II show the number of states dropped from expansion during Likelihood sequence estimation. The number of states of the combined ISI-code trellis dropped from expansion increases at high SNR, and, the number varies as a function of the decision parameter. The curve 1, from right to left show the error performance of 8-QAM uncoded scheme obtained for comparison with the c-PDFD technique.

Fig. 5 show Error Event Probability Vs SNR characteristics obtained for CH11 and the decision parameter x2. The curve No.2 from right is for the SDFSE and it is noted that the error performance is close to that obtained for c-PDFD with a reduced computational complexity. The performance degradation of about 0.4 dB at high SNR is observed at an error event probability rate of 10^{-4}. The curve 1, from left to right, is the error performance of 8-QAM uncoded scheme.

In Fig. 6 error performance characteristics are given for the ISI channel CH12 given in Table I and the decision parameter x1. The characteristic curves show that SDFSE performance is close to that of c-PDFD performance with a small degradation of about 0.2 db at high SNR at an error rate of 10^{-4}. Table. III shows the number of nodes dropped from expansion during SDFSE execution. The number varies as a function of the decision parameter and is larger at high SNR. Fig. 7 depicts the SDFSE error performance characteristic obtained for decision the parameter x2 and for the channel CH12.

Fig. 8 shows the tunable characteristic of SDFSE, obtained as a function of decision parameters x1, x2 and x3 for channel CH11, and, Fig. 9 shows the tunable characteristic of SDFSE obtained for the channel CH12 for the decision parameters x1, x2 and x3. It is observed that as the decision parameter decreases, the SDFSE characteristic approaches the c-PDFD characteristics. The curve 1, from left to right, shows the error performance of 8-QAM uncoded scheme.

The simulation results depicts that error performance characteristics obtained through SDFSE strategy is close to the performances obtained by c-PDFD, with 15 to 20 percent of reduced execution time. The performance is a function of the optimality of the tunable-complexity algorithm which is an integral part of SDFSE. The technique can be extended to complex trellis structures as the execution time is less characteristics. The curve 1, from left to right, shows the error performance of 8-QAM uncoded scheme. To the right, shows the error performance of 8-QAM uncoded scheme.

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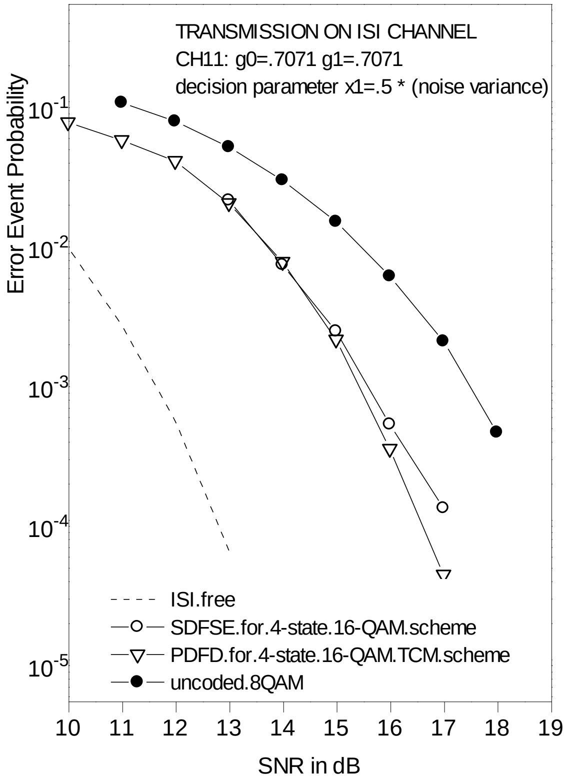

Figure 4. Error Event Probability Vs SNR

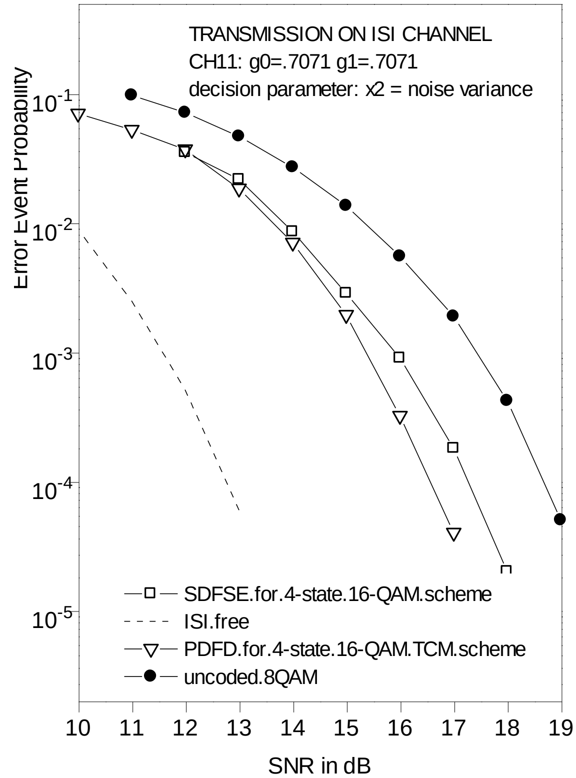

Figure 5. Error Event Probability Vs SNR

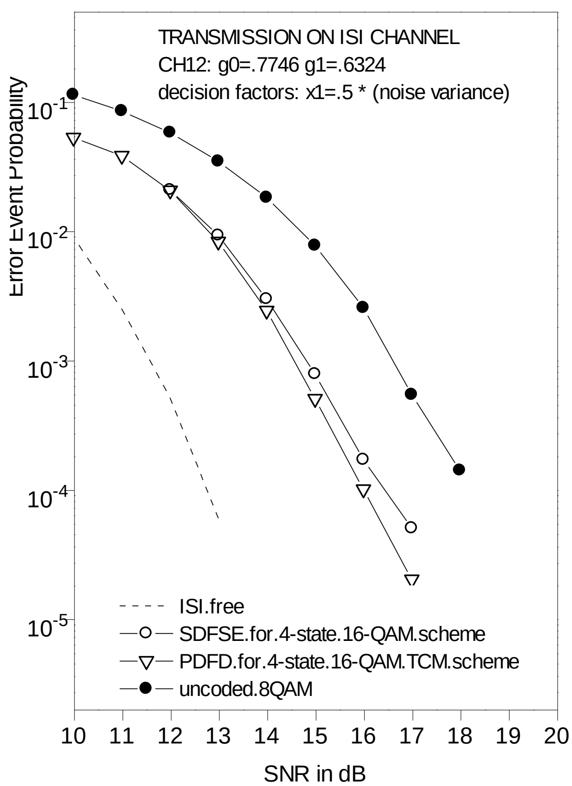

Figure 6. Error Event Probability Vs SNR

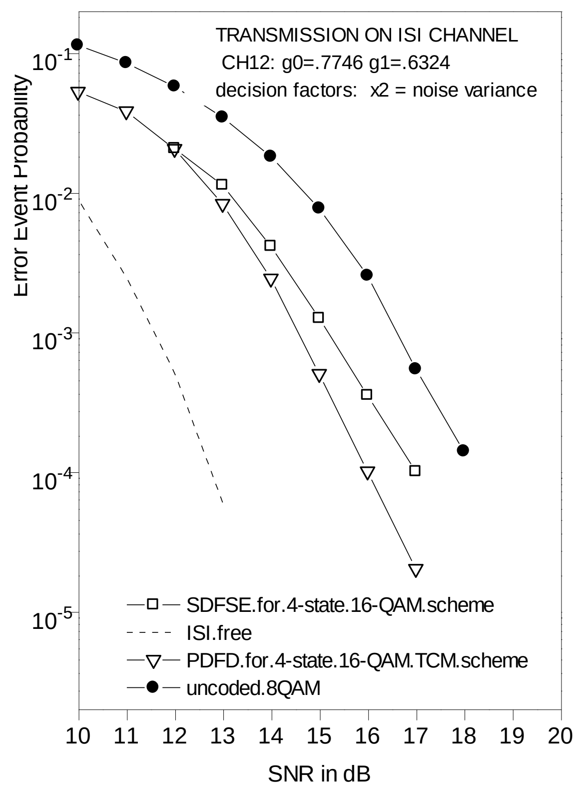

Figure 7. Error Event Probability Vs SNR

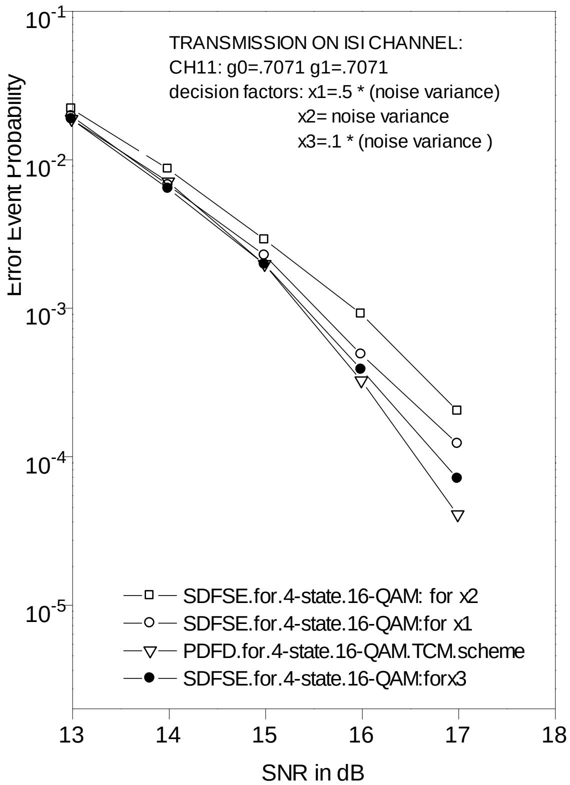

Figure 8. Error Event Probability Vs SNR

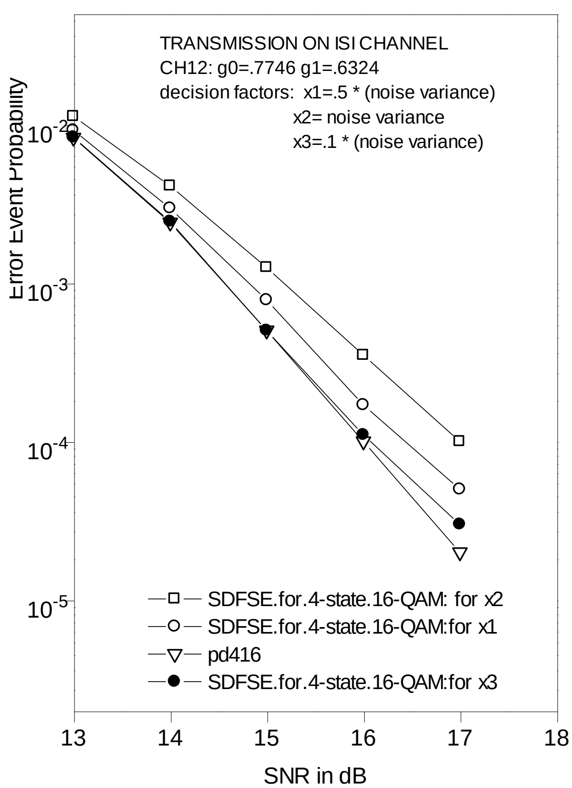

Figure 9. Error Event Probability Vs SNR

TABLE I. ISI CHANNELS AND IMPULSE RESPONSES

Channel	**Impulse Response Coefficients**	
	g0	*g1*
CH11	.707	.707
CH12	.7746	.6324

TABLE II. NUMBER OF STATES DROPPED IN SDFSE

For channel CH11, number of symbols transmitted 10^5		
SNR in dB	*Decision Parameter X=variance*	*Decision Parameter X= 0.5 Variance*
	No. of States not expanded	*No. of States not expanded*
17	13	3
16	34	8
15	100	25
14	229	45
13	434	112

TABLE III. NUMBER OF STATES DROPPED IN SDFSE

For channel CH12, number of symbols transmitted 10^5		
SNR in dB	*Decision Parameter X=variance*	*Decision Parameter X= 0.5 Variance*
	No. of States not expanded	*No. of States not expanded*
17	18	9
16	37	9
15	105	28
14	265	78
13	503	165

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