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Trellis Coded Modulation having Rate 6/7, 128 State with 128 QAM modulation designed for fading Channel

Abstract: - In the realm of constructing digital communication systems, the processes of error correction coding and modulation are often perceived as distinct and autonomous tasks. Modulators primarily focus on encoding information onto carrier signals to enable efficient transmission and optimize bandwidth utilization. Conversely, demodulators are tasked with retrieving the original information from received signals, a process that involves compensating for noise and distortions encountered during transmission. Channel encoding encompasses the transformation of information into a particular code, enhancing its robustness against transmission errors within communication systems. Decoding, conversely, entails the retrieval of the original data from a received encoded signal, including the correction of errors that may have arisen during transmission. In pursuit of enhanced efficiency, a reduction in the code rate is adopted, resulting in increased redundancy within the code. However, this improvement is offset by the necessity for a broader bandwidth. TCM, short for Trellis Coded Modulation, is a transmission method that combines encoding and modulation to achieve substantial coding gain while maintaining bandwidth. This paper presents a novel approach for designing a 128-state rate 6/7 Trellis Coded Modulation (TCM) code, specifically developed for fading channels. The preliminary results demonstrate considerable promise, achieving a coding gain of approximately 10 dB when compared to unencoded 64 QAM. This notable enhancement substantially boosts data rates, particularly in scenarios with constrained bandwidth channels.

Keywords: Trellis Coded Modulation, Convolutional Coding, BER, Channel Coding, QAM

I. INTRODUCTION

For quite some time, the integration of error correction coding methods with compatible modulation schemes has been well-established. Even prior to the introduction of Trellis Coded Modulation, the concept of utilizing multilevel modulation for symbols subjected to convolutional encoding was already recognized [1]. Expanding a signal set not only introduces necessary redundancy for coding purposes but also reduces the spacing between signal points when the average energy remains constant. This phenomenon is visually depicted in Figure 1, showcasing the influence of signal set expansion on the spacing between signal points.

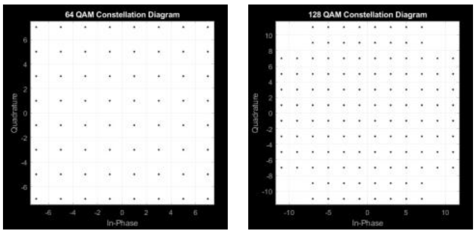

Fig. 1 Expanding a signal set frequently results in a decrease in the separation between signal points

Reduction in gap between the signal points because of enlargement of the signal set can lead to a rise in the error rate [2] and in order to counter this impact, coding methods like Trellis Coded Modulation (TCM) came into existence. TCM is as an effective coding technique that attains coding gain while preserving bandwidth [3], which means that reliable high-data-rate communication is achievable even across the channels having bandwidth constraints. This feature makes TCM especially appealing for terrestrial radio communications, a field where power and spectrum are highly valuable and constrained resources. Fundamental breakthrough of Trellis Coded Modulation is rooted in idea of treating convolutional encoding and modulation as an unified and cohesive process, rather than distinct ones.

This unified strategy enables very good effectiveness and increased efficiency within the transmission system. By combining a modulation scheme with a convolutional code, Trellis Coded Modulation aims to achieve increased noise resistance compared to uncoded transmission. This achievement is realized without necessitating an expansion of signal bandwidth or increased transmission power. The assessment of Trellis Coded Modulation is generally carried out by quantifying the attained coding gain in relation to an unencoded signal. This coding gain

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acts as a measure of improvement in system performance provided by TCM, thereby demonstrating its capacity to counter the channel noise and enhance the communication reliability.

When developing the Trellis Coded Modulation scheme, attention is paid to expand the minimum free distance by forging a connection between the modulation scheme and the trellis configuration. This ensures the capability of the TCM system in optimizing the separation between distinct transmitted symbols, thereby strengthening the code's error correction capabilities. The translation of symbols from the encoder's output to the modulator within Trellis Coded Modulation is not a straightforward because for this mapping, signal constellation is partitioned into discrete signal sets, and symbols are then allocated from these sets. This division of the signal constellation enables efficient encoding along with modulation, leading to increased error correction capabilities and enhanced performance [4]. Within Trellis Coded Modulation, the choice of the signal set is dictated by the encoder's output, while additional systematic input is employed to designate exact symbol within the chosen signal set. This dual procedure involving the selection of signal sets and the mapping of symbols ensures an optimized encoding and modulation arrangement, thereby providing effective error correction and maximizing the overall system efficiency.

Within convolutional codes, one of the foremost and impactful error types is pairwise error. This occurrence becomes obvious when the decoder mistakenly opts for a sequence distinct from the one transmitted by the sender and such errors bear significant consequences on the reliability of the decoding process. These occurrences of pairwise errors in the decoding of convolutional codes can be attributed to inaccuracies in state transitions. To overcome this, a critical step involves the allocation of the constellation points for optimizing the Euclidean distance [5] between diverging and emerging branches. Through the strategic allocation of constellation points to divergent and emergent branches, guided by their Euclidean distances, modulation is seamlessly integrated with the convolutional encoder. This guarantees that the encoding procedure considers the attributes of the modulation scheme, yielding a finely-tuned system that emphasizes on the separation between signal points and improves the error correction capacities. In the Trellis Coded Modulation, detection process relies on soft decision rather than hard decisions. Unlike a binary determination on the received signal, soft decision decoding assesses the probabilities of various symbol values, accounting for both noise and channel conditions. This approach fosters robust decoding, especially when the received signal is corrupted with with noise or interference. In a coded scheme, the utilization of hard-decision demodulation prior to decoding leads to an irretrievable loss of information, resulting in a decline in the Signal-to-Noise Ratio (SNR). Hard-decision demodulation entails binary conclusions about received symbols, thereby discarding valuable insights into the reliability or confidence associated with those received symbols. This information loss can have an adverse effect on the performance of the system, thereby limiting the capabilities to rectify the errors and correct the decoding operation. In fading channel scenarios with soft-decision decoding, when employing maximum likelihood criterion, optimal sequence decoder's decision rule is based on Euclidean distance. The decoder selects sequence with highest likelihood by assessing Euclidean distances between received symbols and potential transmitted symbols. Through this consideration of Euclidean distance, the soft-decision decoder identifies the most probable transmitted sequence. Through the utilization of the Euclidean distance metric, the decoder accurately separates the transmitted sequence that is likely to have been transmitted, while factoring in the impacts of fading, noise, and other channel anomalies. The Trellis Coded Modulation (TCM) with a suitable interleaver yields further coding advantages compared to uncoded schemes, particularly within fading channels however, adhering to well-defined design criteria [6] during the code creation process is very important.

Organization of the paper is as follows. In section II a concise representation of System Model is presented, explaining its key elements and their functioning. Moving forward, Section III introduces the envisaged design methodology and the guidelines for developing the optimum code designed for rate 6/7, 128-State, 128-QAM Trellis Coded Modulation in respect of fading channels. This section provides comprehensive perspectives on the design methodology towards the development of a code that aligns efficiently and effectively with the system parameters. Section IV illustrates the code construction process, detailing each step of its creation. Section V centers on the performance analysis of the suggested design, assessing its efficacy through fading channel. Within Section VI, the outcomes are shown, accompanied by an investigation of the insights gathered from the simulation outcomes. This segment encapsulates an all-encompassing overview of the attained results and their significance concerning the proposed design and the overall system.

II. System Model

Figure 2 presents a comprehensive block diagram outlining the fundamental architecture of a Trellis Coded Modulation scheme [7] deployed within fading multipath channel. The process commences with input bits that undergo encoding via convolutional encoder, generating series of signals (S_i). Each signal corresponds to 6-dimensional vector selected from 128-QAM signal-set, where index 'i' signifies present time index [16]. This diagram serves as an illustrative depiction of the holistic information flow and signal manipulation within the TCM scheme, highlighting the sequential stages of encoding and modulation. Through complex notation, every signal within the Trellis Coded Modulation scheme can be depicted as a point within a complex plane. This presentation offers an accessible means to visualize and dissect the signals. The coded signals can also undergo interleaving, a procedure that reorganizes them to mitigate the burst errors. Interleaving plays a pivotal role in elevating the system's collective error correction capacities and increases the effectiveness of the TCM scheme amidst channel irregularities [8]. Before undergoing modulation and transmission across the channel, it becomes essential to subject the signal to pulse shaping, a process aimed at counteracting Inter-Symbol Interference (ISI). By implementing pulse shaping techniques, the transmitted signal attains a well-defined temporal profile, curbing the likelihood of symbol overlap and diminishing ISI. However, in the course of transmission, the signal unavoidably encounters the influence of Additive White Gaussian Noise, an inherent feature of channel. This noise factor introduces randomness and impacts the overall quality of the received signal.

Upon reception, the received signal undergoes demodulation and quantization to streamline the subsequent decoding phase. Furthermore, a channel estimator may be implemented to gauge the channel's gain, furnishing valuable insights into the channel's state. The inclusion of channel gain estimation empowers the decoder to dynamically adjust its decoding approach to accommodate the ever-changing channel dynamics, thereby increasing the overall system's performance and dependability. The sequence $r_l = (r_1, r_2, \ldots, r_l)$ is used as input for TCM decoder, which conducts Maximum Likelihood (ML) decoding [9]. Employing ML decoding methods, the TCM decoder endeavors to identify the most probable transmitted sequence by analyzing the received sequence of symbols. Through assessing the likelihood of distinct transmitted sequences, the decoder attempts to precisely reconstruct the initial transmitted data, thereby mitigating any errors that might have transpired during the transmission process/ through the channel.

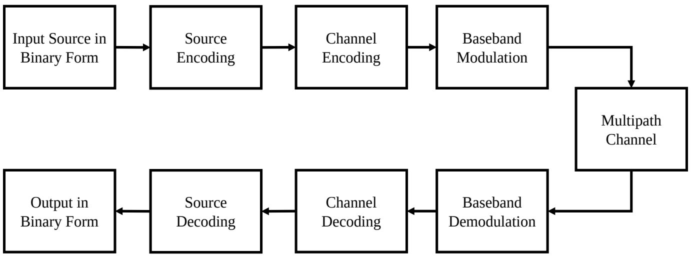

Fig. 2 System block diagram.

Figure 3 illustrates discrete time model that corresponds to system shown in Figure 2. This model provides a representation of received signal at the specific time index 'i', which can be formulated as follows:-

$$r_i = c_i . s_i + n_i \qquad (1)$$

In the eq (1), n_i represents complex Gaussian noise characterized by a mean of zero and a variance of $N_0/2$. Meanwhile, c_i signifies the complex channel gain, also conforming to a Gaussian distribution (complex) with σ_c^2 as variance.

Further, an alternative expression for c_i is:

$$c_i = a_i \cdot e^{j\phi_i} \qquad (2)$$

In the eq (2), a_i denotes the amplitude, and φ_i represents the phase.

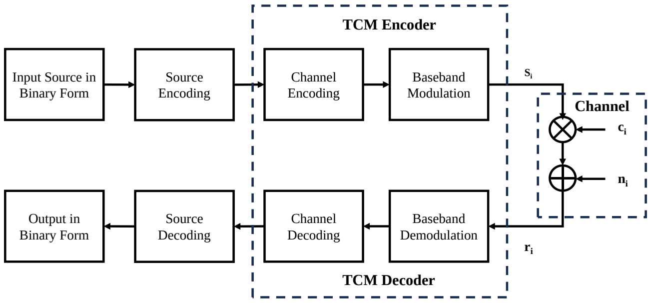

Fig. 3 The system model in Figure 2 represented in baseband

Presuming coherent detection at the receiver, the receiver undertakes compensation for channel's phase shift and therefore, eq (1) can be rewritten as:

$$r_i = a_i s_i + n_i \qquad (3)$$

In eq (3), a_i signifies amplitude of noise.

III. DESIGN

In this section, foundation for designing and building rate 6/7, 128-state Trellis Coded Modulation (TCM) codes for fading channels has been presented. These design rules act as a roadmap for creating TCM codes that can excel in both performance and resilience within the context of fading channel. These rules have been derived from analogous guidelines previously proposed for Trellis Coded Modulation codes designed for fading channels [10,15] having four state and 2/3 rate. Expanding upon these, the rules for designing rate 6/7, 128-state TCM codes have been worked out in order to take care the errors those are introduced by fading channels. Ungerboeck utilized heuristics to design 8-state, Rate 2/3 Trellis Coded Modulation scheme in respect of fading channels [7].

In this paper, a comprehensive set of directives have been presented aiming at formulating 128-state, 128-QAM Trellis Coded Modulation scheme in respect of fading channels [11], which are as follows: -

The signals pertaining to the shifts between states across successive stages are symbolized through a 128 x 128 matrix. Each entry within the matrix corresponds to signal linked with transition from i^{th} state in k^{th} stage to j^{th} state in $(k+1)^{th}$ stage within trellis. This matrix offers an all-inclusive representation of the signal connections and shifts intrinsic to the TCM scheme, facilitating the scrutiny and shaping of the system's architecture. Further, within the matrix, elements of i^{th} row represent signals associated with paths originating from i^{th} state, whereas elements of j^{th} column represent signals associated with paths converging at j^{th} state. This configuration distinctly portrays the flow of signals and the interconnections among distinct states within the TCM scheme.

By employing set partitioning techniques, the 128-QAM signal set can be effectively separated into two distinct subsets: A_0 = {s_0, s_2, s_4, s_6, s_8, s_{10}, s_{12}, s_{14}, s_{16}, s_{18}, s_{20}, s_{22}, s_{24}, s_{26}, s_{28}, s_{30}, s_{32}, s_{34}, s_{36}, s_{38}, s_{40}, s_{42}, s_{44}, s_{46}, s_{48}, s_{50}, s_{52}, s_{54}, s_{56}, s_{58}, s_{60}, s_{62}, s_{64}, s_{66}, s_{68}, s_{70}, s_{72}, s_{74}, s_{76}, s_{78}, s_{80}, s_{82}, s_{84}, s_{86}, s_{88}, s_{90}, s_{92}, s_{94}, s_{96}, s_{98}, s_{100}, s_{102}, s_{104}, s_{106}, s_{108}, s_{110}, s_{112}, s_{114}, s_{116}, s_{118}, s_{120}, s_{122}, s_{124}, s_{126} } and A_1 = {s_1, s_3, s_5, s_7, s_9, s_{11}, s_{13}, s_{15}, s_{17}, s_{19}, s_{21}, s_{23}, s_{25}, s_{27}, s_{29}, s_{31}, s_{33}, s_{35}, s_{37}, s_{39}, s_{41}, s_{43}, s_{45}, s_{47}, s_{49}, s_{51}, s_{53}, s_{55}, s_{57}, s_{59}, s_{61}, s_{63}, s_{65}, s_{67}, s_{69}, s_{71}, s_{73}, s_{75}, s_{77}, s_{79}, s_{81}, s_{83}, s_{85}, s_{87}, s_{89}, s_{91}, s_{93}, s_{95}, s_{97}, s_{99}, s_{101}, s_{103}, s_{105}, s_{107}, s_{109}, s_{111}, s_{113}, s_{115}, s_{117}, s_{119}, s_{121}, s_{123}, s_{125}, s_{127} }. The basis for these subsets lies in their minimum intra-set distance, marked as δ_1. This division streamlines the arrangement and evaluation of the signal set, facilitating the identification and utilization of specific subsets within the TCM framework.

The following set of rules has been introduced to assign signal points to elements within matrix:

a. Initial rule dictates that a signal is restricted to appear once only within designated column or row.

b. The second rule dictates that within a 128-State, Rate 6/7 code, not all transitions are feasible due to the constraint of having only 64 paths originating from each state. Therefore, a signal can be connected to a transition pathway between two states solely if Least Significant Bit of originating state's label corresponds to the identical bit, y ∈ {0, 1}, as Most Significant Bit of target state's label.

c. Corresponding to a given y value, all associated signals must exclusively be selected from either the A_0 or A_1 subset.

IV. Code Construction

This section revolves around the construction of a TCM code designed for a Rate 6/7, 128-State, 128-QAM configuration, adhering to the guidelines described in the preceding section. In accordance with the second guideline, the initial stage encompasses the exclusion of transitions that are impermissible, coupling subset A_0 with a Least Significant Bit (LSB) of 0, and attributing subset A_1 to an LSB of 1. As a result, signals within even-numbered rows will draw from subset A_0, while signals within odd-numbered rows will derive from subset A_1. In this progression, any signal point within subset A_0 can be opted for as initial element of first row. In similar manner, any signal point within A_1 subset can be chosen as the first valid element (corresponding to first feasible transition) of second row in transition matrix. For instance, selecting s_0 from subset A_0 and s_1 from subset A_1 as the respective first elements. In the subsequent phase, signals sourced from subsets A_0 and A_1 are allocated to third, fourth, till 64th row, in accordance with the second guideline.

The subsequent stage involves the option of selecting either s_2 or s_6 as initial element of sixty-fifth row, with the freedom to choose either s_3 or s_7 as first valid element of sixty-sixth row. Through the choice of s_6 and s_7, the remaining signals are systematically allocated to the remaining rows, all in alignment with the second guideline. This marks the finalization of the code's design].

V. Using the Template

The performance analysis considers the scenario where fading amplitudes are independent statistically and channel is memoryless [14]. Probability of error event plays pivotal role in assessing performance of system means lower error event probabilities correlate with less errors, and vice-versa. This section is dedicated to deriving error event probability. Here upper limit of pairwise error probability [12] will be explored. Assuming detection is coherent, Channel State Information is ideal and fading for every symbol is independent, upper limit for pairwise error probability during symbol sequence decoding in a Rician Channel scenario may be formulated as follows: -

$$P_2(S_l, \hat{S}_l) \leq \prod_{i=1}^{l} \frac{(1+K)}{1+K+\frac{1}{4N_0}\left|(S_i-\hat{S}_i)\right|^2} \, e^{\left(-\frac{K\frac{1}{4N_0}\left|(S_i-\hat{S}_i)\right|^2}{1+K+\frac{1}{4N_0}\left|(S_i-\hat{S}_i)\right|^2}\right)} \tag{4}$$

In scenarios characterized by high Signal-to-Noise Ratio (SNR), the above equation simplifies to:

$$P_2(S_l, \hat{S}_l) \leq \prod_{i\in\eta} \frac{(1+K)e^{-K}}{\frac{1}{4N_0}\left|(S_i-\hat{S}_i)\right|^2} \tag{5}$$

The symbol η signifies instances where S_i and $\hat{S}_i$ are unequal. Consequently, equation (5) can be stated as below. Effective length of the error event $(S_l, \hat{S}_l)$ is denoted as l_η.

$$P_2(S_l, \hat{S}_l) \leq \frac{((1+K)e^{-K})^{l_\eta}}{(\frac{1}{4N_0})^{l_\eta} \, d_P^2 l_\eta} \tag{6}$$

$d_P^2(l_\eta)$ denotes square of product distance between signals S_i and $\hat{S}_i$ when these are unequal along error event pathway. This distance is : -

$$d_P^2(l_\eta) = \prod_{i\in\eta}\left|(S_i - \hat{S}_i)\right|^2 \tag{7}$$

Error event occurs when trajectory of received data veers away from intended course as established by design. This concept is visually depicted in Figure 4, where intended trajectory spans from s_1 to s_2 and extends to s_l, whereas trajectory followed by received symbols manifests as $\hat{s}_1$, $\hat{s}_2$, and onward up to $\hat{s}_l$.

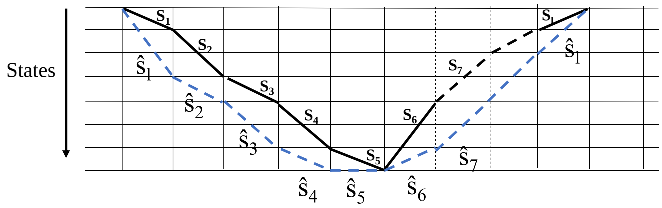

Fig. 4 Error event with a length of l.

By encompassing all sequences those have been transmitted and combining all error events' probabilities across varying lengths l, extending from 1 to infinity, upper limit and upper bound can be formulated as:-

$$P_e \leq \sum_{l=1}^{\infty} \sum_{S_l} \sum_{\hat{S}_l \neq S_l} P(S_l) P_2(S_l, \hat{S}_l) \quad (8)$$

In above equation, $P(S_l)$denotes Apriori Probability of transmitting symbol. At high SNRs, $P_2(S_l, \hat{S}_l)$ can be substituted into equation (8). As a result, upper bound pertinent to Rician fading channel can be articulated in following manner:-

$$P_e \leq \sum_{l_\eta} \sum_{d_P^2 l_\eta} \alpha(l_\eta, d_P^2(l_\eta)) \frac{((1+K)e^{-K})^{l_\eta}}{(\frac{1}{4N_0})^{l_\eta} d_P^2(l_\eta)} \quad (9)$$

Equation (9) signifies that average number of code sequences having an effective length l_η and a squared product distance of $d_P^2(l_\eta)$ is represented by $\alpha(l_\eta, d_P^2(l_\eta))$. When operating at high Signal-to-Noise Ratios (SNRs), error event is affected by l_η and $d_P^2(l_\eta)$. For sake of simplification, we adopt L to symbolize minimum effective length, and $d_P^2(L)$ to denote associated squared product distance. Minimal effective length is regarded as effective length of code, enabling us to approximate probability of error event in the subsequent manner: -

$$P_e \approx \alpha(L, d_P^2(L)) \frac{((1+K)e^{-K})^L}{(\frac{1}{4N_0})^L d_P^2(L)} \quad (10)$$

Regarding the Rayleigh fading channel, in which K equals 0, equation (10) can be further streamlined as:-

$$P_e \approx \frac{\alpha(L, d_P^2(L))}{(\frac{1}{4N_0})^L d_P^2(L)} \quad (11)$$

In context of an AWGN channel, by taking K = ∞, we may reformulate P_e as shown below [12]:-

$$P_e \approx \frac{1}{2} N(d_{free}) erfc\left(\sqrt{\frac{d_{free}^2}{4N_0}}\right) \quad (12)$$

Here, d_{free} denotes value of code's unrestricted Euclidean distance.

Performance evaluation of a Trellis Coded Modulation Scheme [13, 16] within context of Rician Channel has been presented here. Investigation has focused on equation (10) in relation to K (Rician parameter), with an acknowledgment of special cases in which K is either 0 or ∞. TCM involves the application of convolutional encoders at a rate of 6/7. To measure the designed TCM scheme's effectiveness, the achieved results have been compared with those of the uncoded 64 QAM. Decoding has been executed using the Viterbi Decoding algorithm. Figure 8 visually displays BER against SNR for Rate 6/7, 128-State, 128-QAM TCM code, as constructed through the proposed guidelines. Additionally, the BER versus SNR for the uncoded 64-QAM has also been shown within same graph).

VI. Results and Conclusion

The results obtained from analyses show that the proposed technique has led to a significant improvement. Specifically, when compared to uncoded 64-QAM modulation scheme, the designed scheme has produced an increase in Signal-to-Noise Ratio (SNR) over 10 decibels (dB). This improvement in SNR is indicative of the system's increased ability to withstand noise and interference during transmission. In addition, the designed Trellis Coded Modulation coding scheme has enabled the achievement of higher data transfer rates with high reliability. This enhancement is particularly notable when communicating over channels that experience fading, which refers to the fluctuation in signal strength due to factors like multipath propagation or environmental conditions. By incorporating the TCM coding scheme, the communication system becomes more resilient to these fading effects, leading to improved overall performance and enabling transmission of data at higher rates even in challenging channel conditions.

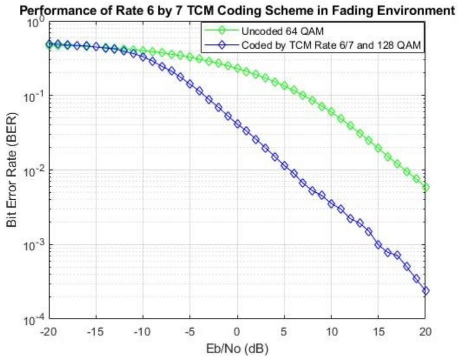

Fig. 5 BER Vs SNR

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