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Trellis Coded Modulation(TCM) System for Satellite Communication:A Review

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ABSTRACT

This paper presents brief review of related literature which describes the TCM scheme and its different design techniques. Study of practicalimplementation of different parts of TCM system likeDifferential encoder, Convolutional Encoder, Mapper, TMU, Viterbi Decoder, De-mapper and Differential Decoder are also discussed.
TCM combines modulation and forward error correction coding in one process to improve the gain over satisfactory BER.One of major application of TCM is satellite communication which is
more prone to bandwidth efficiency instead of power efficiency According to CCSDS [8] recommendation 4D 8PSK TCM is preferred modulation for satellite communication with frequency band 8025-8400 MHz . We found that in TCM system, TCM decoder consumes more power. TCM decoder comprises transition metric unit and viterbi decoder which are highest power consuming modules.
So by optimizing power of TCM decoder satellite communication can become more power efficient.

***Keywords*— TCM (Trellis Coded Modulation), Mapper, Differential Encoder/Decoder, Transition Metric unit (TMU), Viterbi Decoder, Add Compare Select Unit(ACSU), SNR (Signal to Noise Ratio)**

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I. INTRODUCTION

Data transmission over wireless channels are affected by attenuation, distortion, interference and noise that affect the receiver's ability to receive correct information. One of the remedies of this problem is error-correcting coding (ECC).In communication systems, error-correcting coding (ECC) reduces power utilization (i.e., the ratio of the received energy per bit to the noise spectral density) by adding redundancy to the transmitted signal. The performance improvement of the ECC can be achieved by expanding the bandwidth of the transmitted signal in the power-limited region, which requires a high-order modulation scheme. For bandwidth-efficient multilevel amplitude and phase modulation such as PSK or QAM, without expanding the channel bandwidth required by ECC, by increasing the number of signal phase or amplitude over the corresponding modulation constellation performs the same data throughput as un-coded modulation. However this increment requires an additional signal power to maintain the same level of system bit-error-rate. In communications, Trellis-coded modulation (TCM) is applied to solve the conflict of utility efficiency between transmission power and channel bandwidth.

Trellis coded modulation was first invented by Gottfried Ungerboeck .He published his first paper in 1976[1] and followed by more detailed publication in 1982 .Trellis coded modulation was invented as a method which improves noise immunity of digital transmission system without bandwidth expansion and reduction of data rate.TCM scheme employ redundant nonbinary modulation in combination with a finite state encoder which governs the selection of modulation signal to generate coded signal sequence. TCM combines the function of convolutional coder of rate R=k/k+1 and an M-array signal Mapper that maps $M=2^k$input points into $M=2^{k+1}$constellationpoints."Trellis" term is similar to trellis diagram of binary convolution codes but in TCM scheme the trellis branches labeled with redundant non binary modulation signals instead of binary code symbol.At the receiver end noisy signals are decoded by soft decision maximum likelihood sequence decoder.

In this paper Section II explains motivation for TCM scheme. In section III applications of TCM is discussed. Section IV includes designing of 4D 8PSK TCM system. Literaturereview and comparison table of related papers is presented in section V.

II. MOTIVATIION FOR TCM SCHEME

One of the problem described with 8-PSK was "hard" signal decisions made before decoding that causes irreversible loss of information in the receiver. The remedy of this problem is soft decision decoding in that decoder works optimal soft output samples of the channel.

The viterbi algorithm is one of the optimum decoding technique for convolution codes, due to soft decision the notion of error correctionis notappropriate, since there are no hard –demodulator decisions to be corrected. There was no monotonic relation between hamming and Euclidean distance.

For a long time this has been the main reason of lack of good codes for multilevel modulation.

The motivation for developing TCM initially came fromwork on multilevel system that employs the viterbi algorithm to improve signal detection in the presence of intersymbol interference. Due to this work importance of Euclidean distance between sequence comes into picture .It was clear that code should be designed for maximum free Euclidean distance rather than Hamming distance ,and redundancy necessary for coding would have to come from expanding the signal set to avoid bandwidth expansion.

Ungerboeck came up with new and important concept ofmapping by set partitioning which helps in maximizing the free distance. Free distance is an important parameter as it helps in determining the performance of TCM system in terms of probability of error and asymptotic coding gain. Free distance also $d_H$free decides the error correcting capability of coded system. Error correcting capability is given by ($d_H$free -1)/2. As stated earlier TCM scheme improves $d_H$free. so error correcting capability maximizes.

III. APPLICATIONS IN MOBILE AND SATELLITE COMMUNICATION

Before TCM there was no other modulation scheme which achieves significant coding gainfor spectralefficiency 2 bit/sec/Hz and above.For the above mentioned spectral efficiency TCM scheme allows coding gain of 3-6 dB. These are the required gain values which are acceptable by many band limited channels for different applications.With TCM, gap between theory and practice of channel coding has been closed.

The common applications ofTCM are satellite, terrestrialmicrowave and mobile communication.

The rapid progression of mobile communication technology from analog to digital has made available a new variety of services. There is great demand for reliability, mobility and speed in transmission of information. Frequency spectrum is always a limited resource and for its better utilization linear modulation schemes like MPSK are generally used.

MPSK schemes are less power efficient because there is always a tradeoff between power and spectral efficiency .To minimizes the power consumption with required BER, TCM scheme was suggested, withwhichup to 6 dB gain is possible without any bandwidth expansion. Invention of TCM brings golden era in mobile communication.

Multidimensional trellis coded modulation has another important application. It is used for bandwidth-constrained communications between remote satellites and Earth stations [8]. Efficiency in this context, refers both to bandwidth efficiency (in bits/s/Hz and bits/channel-symbol) for a given information quantity, and power efficiency.

According to CCSDS norms for the frequency band 8025-8400 MHz, the recommended modulation is 4D 8 PSK TCM with convolution encoder of code rate 3/4. This application with details of design is described below.

IV. DESIGN OF 4 -D TRELLIS CODED MODULATION(TCM) SYSTEM

TCM scheme is more sensitive to the phase offset than the currently un-coded modulation system. In recent advances TCM scheme uses signal set defined in morethan two dimensions. The best code known as one, two, four and eight dimensional signal sets. In our research work we are considering satellite application with four dimensional TCM. Next part of paper describes designing of 4D 8 PSK TCM system for satellite application.

TCM system comprises of three major parts: TCM Encoding section, Channel and Decoding sections. TCM Encoder system has high-rate convolution encoder to encode the data and Mapper is use to modulate the data. TCM decoding system begins with the sampling of the code word and finishes with the restoring of the original digital source data. TCM scheme is presented in Fig.1.

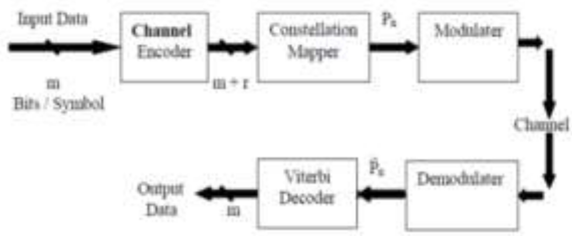

Fig 1. Trellis Coded Modulation Schemes

A. TCM encoder

The design details of convolution encoder and constellation Mapper of 4-D 8PSK TCM system can be found in [5].We need to design convolution encoder of following specification.

1) 64 trellis states;
2) Rate-3/4 convolutional code;
3) Rate of modulation: Rm=m/m+1 where m= 9, 10, or 11.

Construction related details given in [6]. Among the four modulation rates, the case of Rm=10/11 is the most complex one, which dominates the overall computational complexity. Therefore, for simplicity, we only discuss in detail the case of Rm=10/11.

TCM encoder consists of four main parts: a differential encoder, a binary convolutional encoder, a multidimensional Mapper, and a modulator as shown in Fig. 2.

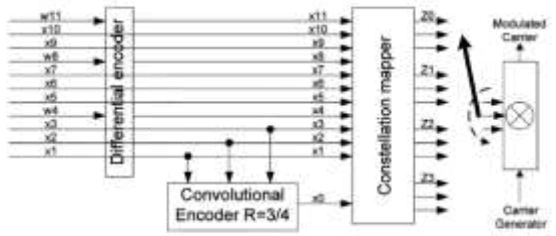

Fig 2.Encoder for 4-D 8PSK for the case of Rm=11/12

The differential encoder is shown in Fig. 3,

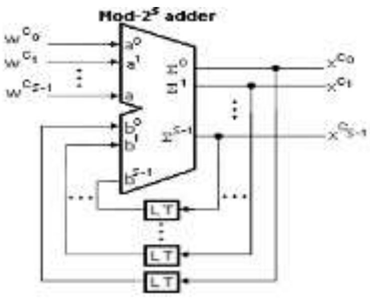

Fig 3. Differential Encoder

The storage elements has a delay of LT where L is the number of 2-D signal set. This system is used for pre-coding theinputs. The basic component of the Pre-coder is the modulo-2^s adder. For most codes this is the Pre-coder to be used. S is the number of bits in affected by phase rotation. Next part of the encoding system is the constellation Mapper which is based on table I. [4]
v

TABLE I
4x8PSK SIGNAL SET PARTITIONING

Partition Level(p)	Ω^p	Minimum Squared subset Distance(Δ^2_p)	Generating vectors$(t^p)_T$
0	Ω(Co,Co,Co)	Min(4,2,0.586)=0.586	$[0\ 0\ 0\ 1]^T$
1	Ω(Co,Co,C1)	Min(4,2,1.1[illegible]	[illegible]
2	Ω(Co,Co,C2)	Min(4,2,1.1[illegible]	[illegible]
3	Ω(Co,Co,C3)	Min(4,2,2.[illegible]	[illegible]
4	Ω(Co,C1,C3)	Min(4,4,2.4[illegible]	[illegible]
5	Ω(Co,C1,C4)	Min(4,4,∞)=4	$[0\ 0\ 2\ 2]^T$
6	Ω(Co,C2,C4)	Min(4,4,∞)=4	$[0\ 2\ 0\ 2]^T$
7	Ω(C0,C3,C4)	Min(4,8,∞)=4	$[0\ 0\ 0\ 4]^T$
8	Ω(C1,C4,C4)	Min(8,8,∞)=8	$[2\ 2\ 2\ 2]^T$
9	Ω(C1,C3,C4)	Min(8,∞,[illegible])=8	$[0\ 0\ 4\ 4]^T$
10	Ω(C2,C4,C4)	Min(8,∞[illegible])=8	$[0\ 4\ 0\ 4]^T$
11	Ω(C3,C4,C4)	Min(16,∞,∞[illegible]	
12	Ω(C4,C4,C4)	Min(∞,∞,∞[illegible]	

Depending on the above table the mapping equation is expressed in (1) . [15]

$$\begin{pmatrix} Z0 \\ Z1 \\ Z2 \\ Z3 \end{pmatrix} = \left\{ (4x^{11}+2x^{8}+x^{4})\begin{pmatrix}1\\1\\1\\1\end{pmatrix} + 4\begin{pmatrix}0\\x^{10}\\x^{9}\\x^{10}+x^{9}+x7\end{pmatrix} + 2\begin{pmatrix}0\\x6\\x5\\x6+x5+x3\end{pmatrix} + \begin{pmatrix}0\\x2\\x1\\x2+x1+x0\end{pmatrix} \right\} (mod\ 8) \quad (1)$$

B. TCM Decoder

Unlikenormal TCM decoder can be divided into 3 parts: the transition metric calculator, the Viterbi decoder and the de-mapper + differential decoder is as shown in the figure 4[5]. The transition metric calculator computes the metric values for the trellis. The Viterbi decoder will find the most probable transition for each step of the trellis. The last part will de-map the selected transition and the path characteristics to find the output word. Implementation of the DMU (De-mapper Unit) and DFD (Differential Decoder) is straightforward; the most challenging and hardware-consuming parts are the VD and TMU.

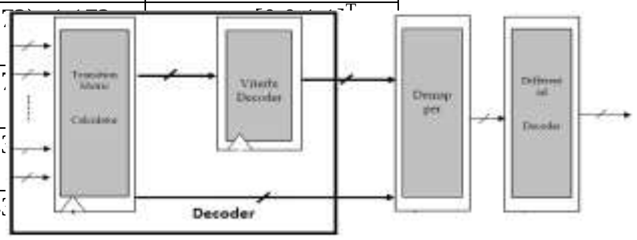

Fig 4.TCM Decoding System [5]

1) TMU(Transition Metric Unit)

In the TCM case, there are parallel paths in state transitions, which extend from one state and end at the same state. For any encoded sequence “x3x2x1x0,” there are 256 different 4-D 8PSK signal groups (combinations of) x11-x4). Therefore, before performing Viterbi decoding, a TMU is used to find the optimal paths among each group of the parallel paths as the BMs. Theoretically, the BM for a soft-decision VD in multidimensional TCM is represented as the sum of the Euclidian distance from each dimension of the signal sets .In a multidimensional TCM decoder, the TMU is very complex and power consuming part.

A Received 8PSK (Ir, Qr) symbol (Is,Qs where s= 0, 1, 2……7 for 8PSK signals). The Euclidian distance is computed asand given in the equation (2).[15]

$ds= (Ir-Is)^2+(Qr-Qs)^2$

$= (Ir^2+Is^2+Qr^2+Qs^2)-2IrIs-2QrQr.$ (2)

Finding the minimum of (the closest constellation point to the received signal) is equivalent to finding the maximum of below equation, Thus we only need to consider the following distance given in equation (3).

$d's=IrIs+QrQs.$(3)

2) Viterbi Decoder

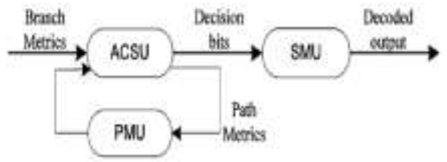

Fig 5.TCM Decoding System

A hardware Viterbi decoder usually consist these parts Branch metric unit (BMU), Path metric unit (PMU) and Traceback unit (TBU).

First, the BMs from the TMU are fed into the add–compare–select unit (ACSU) that recursively computes PMs. Then, the decision bits generated by the ACSU are stored in and retrieved from the survivor-path memory unit (SMU). The PMs of the current iteration are stored in the PM unit (PMU) and read out for use in the next iteration.

3) Demapper

The constellation demapper multiplexes the I ,Q data onto a single bus and passes the serial data stream on to the soft decision calculator .The appropriate metrics for the modulation scheme are calculated .These metrics determine the confidence in the polarity of each constellation bit. These metrics are time multiplexed onto a single bus .The metrics passed on to a quantization module that reduces the bit width of the signal according to a quantization interval.

4) Differential Decoding

It performs the opposite function of differential encoder.

Helps in resolve phase ambiguity.The incoming bits are added together to recreate the input data sequence.

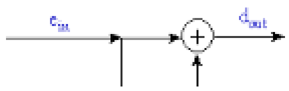

Fig6.TCM Decoding System

V. LITERATURE REVIEW

This section presents literature review on important parameter, techniques and various algorithms used for suggested application. Comparative study of parameters like power dissipation, speed and BER are mentioned in table II.

A. Review of Dimensionality of TCM

TCM is also called as 2LD-MPSK-TCM with L=1, a 2LD modulation with dimensionality factor=1.A method of increasing dimensionality of TCM (L>1) wasproposedin[4].The L term denotes the L dimensions of the 2D MPSK signals. With L=1 we transmit we just 1 TCM symbol. With L=2 transmit just 2 TCM symbol.

Multidimensionality increases the symbol created in one processing period. One of major Advantage of the multidimensionality is that we can transmit fractional information rates .We can reduce the code overhead by affecting more than one symbol so we can use code rates like 5/6,8/9 ,11/12 and so on. It also improves the bit efficiency.

MultidimensionalTCM is suggested as bandwidth efficient modulation [6].

In [5] FPGA implementation of 64 state 4D PSK TCM system was presented which used for high data rate applications and also be able to 4 different code rates:2 bits/symbol, 2.25 bits/symbol, 2.5 bits/symbol and 2.75bits/symbol which all are defined in[6].

In[7] 16 states 2D and 4D TCM codec has been designed on a single chip. This paper presents both FPGA and ASIC implementation of TCM codec.

B. Review for modulation techniques used in TCM

As we know that TCM is the combination of ECC and modulation in one process. Several modulation techniques have been explored for different applications some of review methods are presented below.

*1)QPSK:*QPSK stands for quadrature PSK or 4-PSK. With four phases, QPSK can encode two bits per symbol. In QPSK binary data stream is split into in-phase and quadrature-phase components. These are then separately modulated onto two orthogonal basis functions. In this implementation, two sinusoids are used. Afterwards, the two signals are superimposed, and the resulting signal is the QPSK signal. In [8] for low SNR Gray coded QPSK with convolution rate ½ is preferred to minimize the BER.

*2) 16-QAM:*Quadrature amplitude modulation (QAM) is both an analog and a digital modulation scheme. It conveys two analog message signals, or two digital bit streams, by changing (modulating) the amplitudes of two carrier waves,using the amplitude-shift keying (ASK) digital modulation scheme or amplitude modulation (AM) analog modulation scheme.The QAM modulation is used in such application where high data rate isrequired. 16-QAM is having good BER performance in comparison to QPSK. In[7] 2D and 4D 16–QAM implementation has been discussed for V.32 modem used in satellite communication. In [8] for high SNR 16-QAM modulation with convolution rate 2/3 is used forflexible design of Viterbi decoder for TCM system.

3) 8-PSK: Phase-shift keying (PSK) is a digital modulation scheme that conveys data by changing, or modulating, the phase of a reference signal (the carrier wave).Any number of phases may be used to construct a PSK constellation but 8-PSK is usually the highest order PSK constellation deployed. With more than 8 phases, the error-rate becomes too high and there are better, though more complex, modulations available such as quadrature amplitude modulation (QAM). Although any number of phases may be used, the fact that the constellation must usually deal with binary data means that the number of symbols is usually a power of 2 — this allows an equal number of bits-per-symbol. In [6] bandwidth efficient modulation standards are provided which were approved by management council in June 2001.One of those dedicated to Earth exploration satellite missions, specified in Recommendation 401(2.4.18) B-1. They are applicable to the frequency band 8025-8400 MHz and recommended modulation is 4D -8PSK TCM.In [15] detail and efficient design of 4D- 8PSK TCM is given.

*4) 64-QAM:*QAM, Quadrature amplitude modulation is widely used in many digital data radio communications and data communications applications.64-QAM may be used when data-rates beyond those offered by 8-PSK are required by a radio communications system. This is because QAM achieves a greater distance between adjacent points in the I-Q plane by distributing the points more evenly and in this way the points on the constellation are more distinct and data errors are reduced. In[8] flexible Viterbi decoder is presented which can adapt to varying channel conditions. The third mode uses TCM with 64-QAM.

C. Review of various techniques and algorithms

Basic concept of TCM is presented in [1], lot evolution has been suggested till now. In this section year wisetechnology review is presented.

As we know TCM is very important concept for high speed wireless applications and decoder must work with high clock frequency. In [4] TCM decoder has been implemented with auxiliary trellis based concept which achieve the peak data rate of 460Mbps.Moreover this decoder should also be able to decode4 different modulation rates: 2 bits/symbol, 2.25 bits/symbol, 2.5 bits/symbol and 2.75bits/symbol which are all defined by the CCSDS.
In [7] a new technique of implementation of very large scale integration trellis coded modulation is presented,to simplifythe decoding algorithm and calculation, branch cost distancesare pre-calculated and stored in a distance look-up table (DLUT).Theconcept of DLUT significantlyreduces hardware requirements. The technique was used to design a 16-state, radix-4 codecfor two-dimensional and four-dimensional TCM. Implementation details and decoding speed mention in the table II.
In [11] a low-complexity, high-speed 4-dimensional 8-ary Phase Shift Keying Trellis Coded Modulation (4-D 8PSK TCM) decoder. In the design, an efficient architecture for the transition metrics unit (TMU) is proposed to significantly reducethe computation complexity without degrading the performance. Pipelining and Parallel processing techniques are exploited to increase the decoding throughput. In FPGA implementation of the TCM decoder can achieve a maximum throughput of 1.062 Gbps.
In [12] an efficient architecture based on pre-computation for ACSU unit of Viterbi decoder incorporating T-algorithm. Through optimization at both algorithm level and architecture level, the new architecture greatly shortens the long critical path introduced by the conventional T-algorithm. Using this proposed technique we achieved more than twice improvement in clock speed with negligible computation overhead while maintaining decoding performance.
In [13]Low complexity architecture for the transition metric unit of TCM decoder is proposed based on substructure sharing. A new hybrid T-algorithm for a Viterbi decoderis developed by applying a T -algorithm on both branch metrics (BMs) and path metrics (PMs). TCM encoders usually yield many more transition paths per state. By purging unnecessary additions on BMs and Applying the algorithm on BMs instead of PMs allows one to move the “search-for-the-optimal” operation out of the add–compare– select-unit (ACSU) loopthe hybrid T-algorithm can reduce the computations required with the conventional T -algorithm on PMs by as much as 50%.

In[15] high-speed, low-power design of Viterbi decoders for 4D 8 PSK trellis coded modulation (TCM) systems is presented. Encoder rate is ¾ .It is well known that the Viterbi decoder (VD) is the dominant module determining the overall power consumption of TCM decoders. Pre-computation architecture incorporated with T-algorithm for VD, which can effectively reduce the power consumption without degrading the decoding speed much. The pre-computation architecture reduces the power consumption by as much as 70% without performance loss, while the degradation in clock speed is negligible.

TABLE II
COMPARISON OF IMPLEMENTATION

Paper	**Platform**	**Algorithm**	**Data Rate**	**BER dB**	**Power mW**
[6]	FPGA	Auxiliary Trellis Structure for theTMU	460 Mbps	10.8	21.3
[7]	ASIC 0.18µm	DLUT,and OLUTs	1 Gbps		
[12]	Xc4vlx160-12ff1148 Virtexspeed scale 12	Pipelining and Parallel Processing Techniques	772 Mbps	13.3	
[13]	Virtex-4 FPGA (XC4VLX160).	Hybrid T Algorithm	631.7 Mbps	<11	
[15]	Synopsys Tool with TSMC 90nm standard cell.	Two step Precomputation	446.4 Mbps	<11 dB	6.6127

Paper	Platform	Algorithm	Data Rate	BER dB	Power mW
[16]	Xilinx 6vlx75tff484-1 with speed grade 1	Two step Precomputation	333.76 Mbps	<11 dB	

In [16]Add-Compare-Select loop is modified using the pre-computation architecture. This shortens the long critical path introduced by the conventional T-algorithm. Register exchange algorithm is used for the survivor memory unit design, since it is faster and requires lesser memory. Conceptually, Register exchange algorithm has a pre-defined end state. Since the optimized T-algorithm is used, pre-defining the end state is not possible. This issue is focused and appropriate solution isprovided in this paper. Here RE scheme with survival length of 36 is used for SMU which helps in reducing power consumptions. Hardware details and other parameters mentioned in the table II.

V. LITERATURE REVIEW

After reviewing papers we found that TCM is bandwidth efficient modulation it conserve bandwidth by doubling the constellation points of the signal.

Later on we discussed Basic concept of 4D -8PSK TCM suggested by CCSDS used for satellite application. After reviewing related papers we come to know that TCM decoder is the highest power consuming module of TCM system. There is always a tradeoff between power and speed. After analyzing results of existing work we come to conclusion that further optimization of power can be possible with required speed and gain.So in our research work we shall focus on power optimization of TCM decoder by applying suitable power reduction technique.

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