APPLICATION OF TRELLIS CODES FOR PRIMARY RATE ISDN

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ABSTRACT

We introduce Trellis-coded modulation, used for data communication with the purpose of gaining noise immunity over uncoded transmission without altering the data rate. Trellis-coded modulation is a combined coding and modulation scheme for improving the reliability of a digital transmission system without increasing the transmitted power or the required bandwidth. The trellis code solution combines the choice of a higher-order modulation scheme with that of convolutional code. A significant coding gains can be accomplished without compromising bandwidth efficiency. In this paper, we study the effect of trellis encoding algorithms, and evaluate its effectiveness on three loops with different topology in presence of imperfect Echo Cancelers (EC), for primary rate ISDN application. These loops are selected from a practical and existing Data Base Loop Environment (DBLE) used in the United States of America. The loop topologies are discussed. A basic methodology for the simulation of trellis codes for Quadrature Amplitude Modulation (QAM) clusters is studied. The effect of trellis codes for 16- and 64-QAM is presented. The coded 16- and 64-QAM constellations for the three sample loops under various echo cancellations (55, 60, 65, 70, and 75 dB) are compared and presented.

Keywords: Application, Trellis, Codes, Priway-IDSDN.

1. INTRODUCTION

The Quadrature Amplitude Modulation (QAM) is one of the viable bandwidth efficient codes in which data are coded in two orthogonal components in the time dimensions. In these codes, a selected number of binary bits are encoded as a symbol. When the amplitude is held constant at $2^{1/2}$, the symbol may have a real (in-phase) and an imaginary (quadrature) component, thus leading to the simplest 4 point cluster (1,1; -1,1; -1,-1; 1,-1), with two binary bits being encoded as one of the four cluster points. If the amplitude also can be used as an information carrying parameter, then the family of cluster points may be used.

Generally, the X (in-phase) and Y (quadrature) components can also be directly encoded. This freedom to encode the two components independently permits 3 binary bits to be encoded as an 8-point point cluster, 4 bits to be encoded as a 16-point cluster, or n bits to be encoded as a 2^n point cluster.

In practice, the balanced clusters (e.g., 4, 16, 64, etc., 8-PSK, 32-CROSS, 128-CROSS and so on) are favored since the transmission medium (i.e., the twisted wire pairs) can treat the in-phase and quadrature components, and also the positive and negative signal levels, alike [1].

QAM techniques are being considered for use with the existing twisted wire pairs to transmit data to the subscriber premises at 1.544 Mbit/s (T1 Rate). Many line codes and variations of line codes were studied by the Exchange Carrier Standard Association (ECSA), that led to the choice of the 2B1Q line code (every two bits of input signal are represented by a four-level or Quaternary line signal) as the North American Standard for Basic Access DSLs. (Digital subsuiber lines). The studies assumed that Adaptive Echo Cancelers (AEC) and Decision Feedback Equalizers (DFE) were used in the transceivers [2].

In the application envisaged in this study, a 16- and 64-point cluster are considered, which in turn limits the required symbol rate of the transmission medium to about 386 and 257 kilobauds (kbauds), respectively, corresponding to T1 transmission rate (1.544 Mb/s), or about 512 and 340 kbauds, respectively, corresponding to E1 transmission rate (2.048 Mb/s) used in Europe. With this limited bandwidth, higher bit rates over subscriber loops without repeaters (and loading coils) are feasible, and for this reason it is envisioned that the primary rate ISDN services can be made available to most CSA subscribers.

2. TRELLIS CODES OF INTEREST

Trellis-coded modulation has evolved as a combined coding and modulation technique for digital transmission over bandlimited channels. Its main attraction comes from the fact that it allows the achievement of significant coding gains over conventional uncoded multilevel modulation without compromising bandwidth efficiency.

Trellis schemes employ redundant nonbinary modulation in combination with a finite-state encoder, which controls the selection of modulation signals to generate coded alphabet sequences. In the receiver, the noisy signals are decoded by a soft-decision maximum-likelihood sequence decoder. Simple four-state trellis schemes can improve the robustness of digital transmission against additive noise by 3 dB, compared to the conventional uncoded modulation. With more complex trellis schemes, the coding gain can reach a maximum of 6.28 dB [3].

These gains are obtained without bandwidth expansion or reduction of the information rate as required by traditional error-correction schemes. The term "Trellis" is used because these schemes can be described by a state transition (Trellis) diagram similar to the trellis diagrams of binary convolutional codes.

The difference is that in trellis schemes, the trellis branches are labeled with redundant nonbinary modulation signals, rather than with binary code symbols.

Detailed results of this simulation study under various conditions of the loops and bit rates at various echo cancellation values are presented here.

3. CSA LOOP ENVIRONMENT

There are four dominant wire sizes used. The finest diameter wire generally encountered is the # 26 American Wire Gauge (AWG), roughly equivalent to the 0.4039 mm wire used in European countries. The coarsest wire is the # 19 AWG with a diameter of 0.9119 mm. The two intermediate wire sizes used in the loop plant are the # 24 AWG (0.5105 mm) and the # 22 AWG (0.6426 mm).

The United States, Australia, The United Kingdom, and most Western European countries all have telephone networks in which a number of different diameters of the wires mentioned above are used. This produces gauge changes in the subscriber loop plant. The junction points between wires of different diameters are sources of reflection, and constitute nonuniformity in the cable characteristics.

Open circuited cable sections tapped off the main loop between the central office and the subscriber known as bridged taps (BT's) are also abundant in the United States, Canada, Japan, Italy, and Australia. In the other Western European countries, the data on bridged taps have not been published.

Combined gauge discontinuities and bridged taps are generally present in the United States, Japan, Canada, Italy, and Australia. Hence the system tailored for the bridged taps should also accommodate discontinuities that result from gauge changes [4].

The Data Base Loop Environment (DBLE), or sometimes called the 1983 Loop Survey, consisted of a random sample of 2290 loops from the participating Bell Operating Companies. The survey indicates that about 23.7% of the sampled loops are loaded, and thus unfit for ISDN access. This removes 543 loops from the survey with 1747 loops remaining for ISDN considerations. However, 227 loop configurations either do not carry accurate description for the analysis of the proposed ISDN services, or are longer than 18,000 feet, or are loops that have non-standard cable make-up, thus further reducing the subset to 1520 loops (about 66% of the total sampled loops) considered for the ISDN rates, these ISDN loops are nonloaded and less than 18,000 ft., and have standard cable sections.

The loop environment is far from the ideal situation where uniform gauge wires run from the central office to the subscriber. Any design of a bidirectional data transmission facility has to accommodate the wide disparity of cable compositions, bridged tap configurations and variable impedances of the loop.

A Carrier Serving Area (CSA) is a plant engineering entity, a distinct geographic area capable of being served by a single theoretical Remote Terminal (RT). However, the following two recent developments have made the investigation in this paper convenient and relevant.

First, the market study for the need of the T1 rate data services, and the location of the customers, suggests that these high data rate customers are located well within the carrier serving area (CSA), or close to the central offices. The loop length is thus restricted to a maximum length of 12 kft (3.6 km) or equivalently, loss is limited to the average loss of 9 kft (2.7 km) of 26 AWG twisted wire pair in the traditional telephone cable network. The carrier serving area (CSA) loops have to meet the five following requirements:

(1) There is no loading coils anywhere in the loop;
(2) Any loop containing # 26 AWG (American Wire Gauge) is restricted to a total length of 9 kft (2.7 km.), including bridged tap (BT) length;
(3) If there is no # 26 AWG in the loop, its total length of all 24, 22, and 19 gauge cables in the loop (including all BT's) may be as much as 12 kft (3.6 km.) beyond the theoretical RT site on nonloaded coarse gauge loops;
(4) Total BT's length is limited to 2.5 kft, with no single tap greater than 2.0 kft;
(5) The number of gauges is limited to two (exclusive of BT's) along the loop [5].

Therefore, the loop configuration is likely to be simpler with zero, one or two bridged taps (BT's), as defined by the CSA loop selection criteria.

The entire 1983 loop survey database is not published. However, its statistics have been published extensively. For this reason, we have developed a pseudo loop survey database whose statistics are in total conformity with the well publicized 1983 Bell System loop survey statistics. The loop selection criteria imposed for the CSA loops curtails the 2290 loops (1983 pseudo loop survey) down to about 350 loops, which constitute the Pseudo Carrier Serving Area database (PCSA).

Due to loop asymmetry, the two ends of the loop can exhibit entirely different responses, since the bridged taps tend to exist closer to the subscriber. Thus the need for adaptation becomes essential to cope with the loop, its gauges, its discontinuities in the wire gauges, and the presence of bridged taps.

Second, the study of bandwidth-efficient Quadrature Amplitude Modulation (QAM) codes, has indicated that these codes, traditionally used in microwave carrier systems and voiceband modems, may also have an application in high-speed data transmission.

The results produced by applying trellis code on three loops with different topologies, selected from the PCSA loop database are presented in this paper. These loops exhibit different behavior, from loops with fewer discontinuities and no bridged taps (e.g. loop 1), to loops with more discontinuities and up to two bridged taps (e.g. loop 3) as described by the CSA design rules, the second loop (loop 2) is an intermediate one.

With this choice, we were able to classify the PCSA loop database into three different classes, and estimate the behavior for the other loops within this PCSA database.

A sample of the loops selected from the PCSA database are depicted in Figure (1).

4. SIMULATION CAPABILITY

The simulation facility organized around the databases offers significant potential to study the effects of changing the design of the system, or the design of components and studying the incremental effects of changing parameters to optimize their values. In the design of a system and the design of components (filters, equalizers, terminating impedances), both the spectral and the time domain simulation facilities are extensively used. In studying the effects of different codes, the time domain simulation facility is extensively used. The simulation capability also encloses an elaborate graphic software system. Numerous and diversified results are obtained from the facility. Hence, a systematic method of illustrating and listing the results becomes essential. Individually tailored software to generate specific displays is also coded, altered, and updated to suit design requirements.

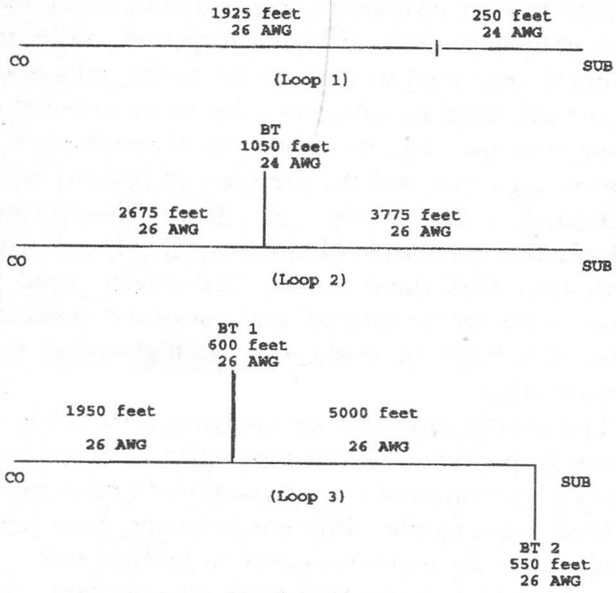

Figure 1. Loop configurations.

Three rectangular Quadrature Amplitude Modulation (QAM) signal formats with four, sixteen, and sixty four points are considered. Data is transmitted bidirectionally leading the two sets of clusters (subscriber and central office sides), for each simulation run. The four point cluster is formed at (1,1), (-1,1), (-1,-1), and (1,-1) points, where each of the two data bits (00, 01, 10, 11) are placed. This leads to a bit rate of about 800 kilobauds (kbauds) for T1 (1.544 Mb/s) rate. This rate is the same if 2B1Q code, already accepted for Basic Rate (BR) ISDN access in the US is used. For this reason, results of the loop performance with four point clusters is not presented. However, for the 16- and the 64-point clusters, the symbol rates become 386 kbauds (1544/4 with $2^4 = 16$), and approximately 257 kbauds (1544/6 with $2^6 = 64$), respectively.

The simulation applies 8192 random symbols for each run. The actual number of information bits to generate any point in the 16, and 64 constellation symbol are 4 and 6, respectively. Fast Fourier Transforms (FFT) are used to reduce the running time for each loop. Further, the harmonics of the excitation function are computed, and stored away for simulations on several loops. The computational software uses three overlays to conserve computer memory. The first overlay generates random symbols and computes the harmonics. The second overlay, simulates the system performance and generates the received QAM clusters as numeric data. The third overlay, exemplifies the results on color displays as QAM clusters.

The primary goal in establishing the simulation software for any network facility, is to evaluate the capability of the entire loop population in any subscriber loop database (such as CSA loop database), with the various types of QAM and trellis codes. System performance with various transmission techniques and associated system components, such as equalizers, echo cancelers, and timing recovery circuits.

5. RESULTS

5.1 *16-QAM/8-PSK RESULTS*

The trellis-coded modulation techniques are introduced for data communication with the purpose of gaining noise immunity over uncoded transmission. It also improves the reliability of a digital transmission system without increasing the transmitted power or the required bandwidth. For example, the 16-QAM using trellis code, is compared to the uncoded 8-PSK using the Primary Rate (PR) or T1 rate (1.544 Mb/s) because of the following:

In the 16-QAM coded scheme, 3 bits per symbol are applied to the convolutional encoder to add an extra bit producing 4 bits, which are then applied to the line coder to generate $2^4 = 16$ points cluster. The transmission rate is 1.544/3 = 514.67 Kilobauds (kbauds). The typical rate used in the simulation studies is approximated to 520 Kbauds.

In the 8-PSK uncoded scheme, however, 3 bits per symbol are applied directly to the line coder, which produces $2^3 = 8$ points cluster. The transmission rate is 1.544/3 = 514.67 Kbauds. The rate used is 520 Kbauds.

In both cases, the same rate is transmitted, providing a fair comparison leading to a proper computation of the coding gain.

In this section, we present the simulated 16-QAM clusters for the three loops shown in Figure (1). The 8-PSK simulations at 60 dB EC are used to calculate the noise in every point in each cluster. The noise is assumed to be the distance every point deviates from its ideal position, the eight ideal locations are situated on a circle of unit radius at 45° intervals. After the noise in every point in the cluster is calculated, the average noise in the entire cluster is computed, and then used to calculate the gain in the 16-QAM clusters at 60 dB Echo Cancellation (EC).

The 16 points are located at (1,1; 3,1; 3,3; and 1,3 in the first quadrant) and at image locations in the second, third, and fourth quadrant in the constellation. By examining the clusters for each loop at different EC values, we notice the following:

For Loop 1, illustrated in Figure (1), it consists of two sections: 26 AWG and 24 AWG, no Bridged Taps (BT's) exist in this loop. Therefore, there are no reflected signals. This loop is particularly short (2175 feet), and does not cause a serious cluster noise with 50 dB, 60 dB, and 70 dB echo cancellation. Note that this loop is qualified to carry the Primary Rate ISDN (PR-ISDN) for the three EC values 50, 60, and 70 dB. The 16-QAM cluster for loop 1 is not noisy, since all points are almost in their ideal positions.

Loop 2 is longer than loop 1. It consists of three sections, two of which are the main loop (6450 feet of 26 AWG) and one BT (1050 feet of 24 AWG). As expected, the cluster noise which occurs in both sides decreases as the EC value is increased from 50 to 70 dB. The cluster at 70 dB EC has the points concentrated in the middle of each square. It should also be expected that there is almost no difference between the two sides of this loop. This is due to the fact that the BT is located nearly in the middle of the loop (but closer to the Central Office (CO) side). This loop also succeeds to carry the PR-ISDN at all EC values 50, 60, and 70 dB. The 16-QAM cluster for loop 2 is illustrated in Figure (2) for the subscriber side.

Loop 3 is a little longer than loop 2. It has four sections, two of which are the main loop (6950 feet of 26 AWG). However, two BT's exist here (1150 feet of 26 AWG) producing more reflection, at 50 dB EC the points are dispersed all over the plot. As a consequence, this loop fails to carry the Primary Rate ISDN (PR-ISDN). The plot improves as we increase the EC value to 60 dB, but also fails to carry the PR-ISDN at this stage. At 70 dB, however, the loop successfully carries the PR-ISDN. The 16-QAM cluster for loop 3 at 60 dB EC is shown in Figure (3) for the subscriber side.

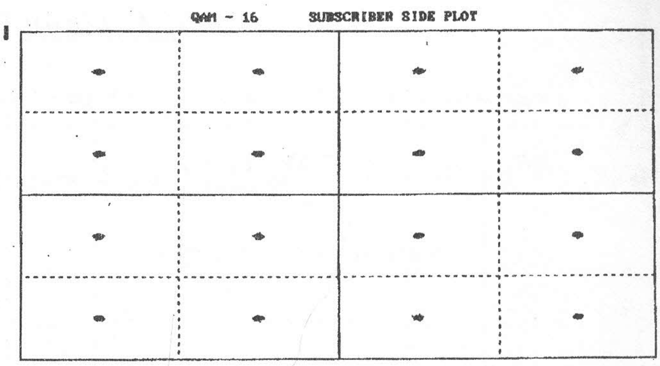

Figure 2. 16-QAM for loop 2 at 60 dB EC (SUB side).

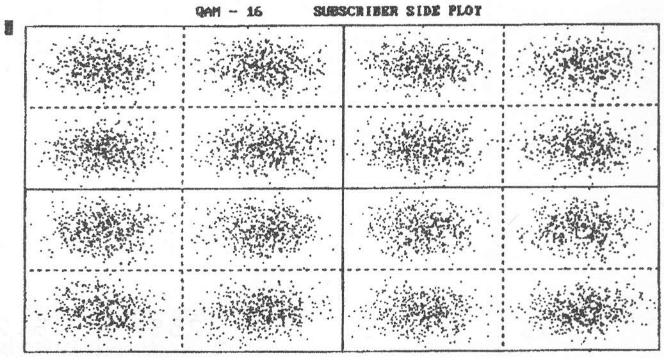

Figure 3. 16-QAM for loop 3 at 60 dB EC (SUB side).

Only the subscriber side clusters are shown, since they tend to be noisier due to the bridged taps being closer to the subscriber end. The trellis gains at both sides for the three loops for various echo cancellations are presented in Table (1).

5.2 *64-QAM/32-CROSS RESULTS*

The 64-QAM using trellis code is compared to the uncoded 32-CROSS using the Primary Rate (PR) or T1 rate (1.544 Mb/s) because of the following considerations:

Table 1 Gain 16-QAM/8-PSK [dB]

EC	LOOP 1 (no BT)		LOOP 2 (1 BT)		LOOP 3 (2 BT)	
(dB)	SUB	CO	SUB	CO	SUB	CO
55	5.2980	5.3082	4.8966	4.8007	error	2.8894
60	5.3133	5.3189	5.0960	5.0456	error	4.1084
65	5.3221	5.3255	5.2026	5.1756	2.2406	4.6861
70	5.3263	5.3283	5.2601	5.2440	3.8438	4.9744
75	5.3293	5.3299	5.2917	5.2835	4.5655	5.1350

In the 64-QAM coded scheme, 5 bits per symbol are applied to the convolutional encoder to add an extra bit, producing 6 bits, which are then applied to the line coder to generate $2^6 = 64$ points cluster. The transmission rate is 1.544/5 = 308.8 Kilobauds (kbauds). The typical rate used in our simulation studies is approximated to 310 Kbauds.

In the 32-CROSS uncoded scheme, however, 5 bits per symbol are applied directly to the line coder, which produces $2^5 = 32$ points cluster. The transmission rate is 1.544/5 = 308.8 Kbauds. The rate used is 310 Kbauds.

In both cases, the same rate is transmitted providing a fair comparison and computation of the coding gain.

This paper presents the results from extensive simulations, the transmission rate being enhanced to the primary rate with Quadrature Amplitude Modulation (QAM) and trellis encoding algorithms. A series of results, indicating the improvement of 64 point trellis constellations codes as the Echo Cancellation (EC) is increased from 50 dB to 70 dB, are presented. These results depend upon the loop environment and the system components that constitute the entire transmission system.

In this section, we present the simulated 64-QAM clusters for the three loops shown in Figure (1). The 32-CROSS simulations at 60 dB EC are used to calculate the noise in every point in each cluster. After the noise in every point in the cluster is calculated, the average noise in the entire cluster is computed for the purpose of calculating the gain in the 64-QAM clusters at 60 dB Echo Cancellation (EC). Typical examples of 64-QAM clusters using trellis codes at 60 dB Echo Cancellations (EC) for the three typical CSA loops mentioned are also presented.

The 64 points are located at (1,1; 3,1; 5,1; 7,1; 1,3; 3,3; 5,3; 7,3; 1,5; 3,5; 5,5; 7,5; 1,7; 3,7; 5,7; and 7,7 in the first quadrant) and at image locations in the second, third, and fourth quadrant in the constellation. The cluster for the coded 64-QAM for loop 1 is not noisy. However, clusters for loops 2 and 3 have considerable noise (Figures (4) and (5)). Only the subscriber side clusters are shown, since they tend to be noisier due to the bridged taps being closer to the subscriber end. The trellis gains at both sides for the three loops under various conditions are presented in Table (2).

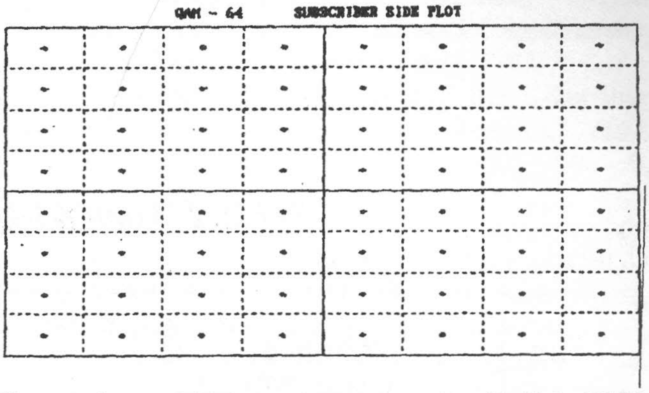

Figure 4. 64-QAM for loop 2 at 60 dB EC (SUB side).

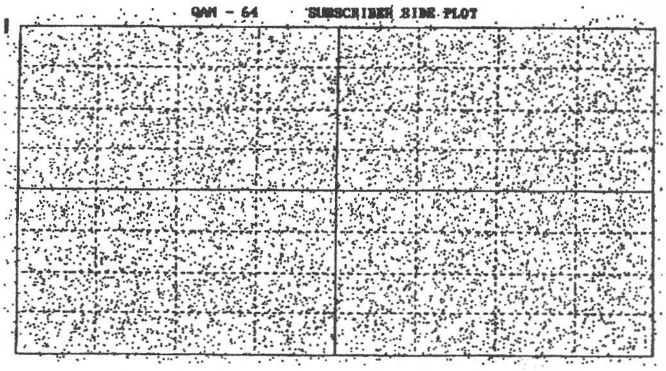

Figure 5. 64-QAM for loop 3 at 60 dB EC (SUB side).

6. CONCLUSION

This paper studies the effect of trellis encoding algorithms in a typical Carrier Serving Area loop environment. We combine the effects of the components and their practical limitation of realizability with the predicted advantages of the well known trellis codes.

The 16- and 64-QAM constellations have been presented throughout this study. The response of the three sample loops selected from a typical CSA loop environment has also been presented. For each constellation, the average noise in both schemes (i.e., coded and uncoded) has been calculated. The coding gains for the 16- and 64-QAM using trellis codes are evaluated with respect to the uncoded 8-PSK and 32-CROSS schemes, respectively.

We have seen that the trellis-coded schemes are influenced by the loop topology and the BT's locations. Their effect can be noticed from Figures (2) and (3), for loops 2 and 3 respectively.

Table 2 Gain 64-QAM/32-CROSS [dB]

EC	**LOOP 1** (no BT)		**LOOP 2** (1 BT)		**LOOP 3** (2 BT)	
(dB)	SUB	CO	SUB	CO	SUB	CO
55	3.6850	3.6953	3.1918	3.1408	error	error
60	3.7215	3.7273	3.4555	3.4285	error	1.7648
65	3.7417	3.7448	3.5963	3.5817	error	2.7965
70	3.7528	3.7547	3.6704	3.6626	0.4468	3.2503
75	3.7592	3.7600	3.7133	3.7089	2.2768	3.4878

In effect, the paper evaluates the performance of the system components weighed against the noise advantage of the coding algorithms in the practical loops.

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