PERFORMANCE EVALUATION OF TRELLIS CODES ON THE CARRIER SERVING AREA LOOP ENVIRONMENT

Ahmed R. Khalifa and Sayed A. Nouh
Computer and Systems Department, Faculty of Engineering,
University of Al-Azhar, Cairo, EGYPT

ABSTRACT

Trellis-coded modulation has evolved over the past few years as a combined coding and modulation technique for digital transmission over bandlimited channels. In a bandwidth-limited environment, increased efficiency in frequency utilization can be obtained by choosing higher-order modulation schemes (e.g., 8-PSK instead of 4-PSK), but a larger signal power would be needed to maintain the same signal separation and hence the same error probability. In this paper, we are presenting the effect of trellis encoding algorithm on the Carrier Serving Area (CSA) loop environment, this loop environment consists of about 350 loops. A loop selection criteria is presented, which is used to select these loops from a larger loop database survey. The results in this paper are based upon the entire CSA loops. We are also drawing a comparison from purely transmission consideration of how well the coded trellis at the Primary Rate Integrated Services Digital Network PR-ISDN (1.544 Mbit/s) compares to the uncoded scheme at the lower symbol rate for the same data rate of 1.544 Mbit/s. We are presenting figures illustrating the Signal to Noise Ratio (SNR) for the entire CSA database, for coded and uncoded 16- and 64-QAM.

Keywords: Performance, Trellis, Codes, CSA, Loop.

1. INTRODUCTION

Quadrature Amplitude Modulation (QAM) or *Quadrature Amplitude Shift Keying (QASK)* is a combined amplitude and phase modulation scheme. Consider an alphabet that is a list of complex numbers, for example A = {-1,-j,+1,+j}. This example alphabet has size M = 4; each symbol can represent $\log_2 M = 2$ bits.

A complex-valued alphabet is best described by plotting the alphabet as a set of points in a complex plane. Such a plot is called a signal constellation. Note that the two terms constellations and clusters are equivalent, they are used interchangeably throughout the paper. There is a one-to-one correspondence between the points in the constellation and the signal alphabet.

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). The American telephone network has a metallic connection to most of the customers from the central office or a remote distribution facility. Enhanced use of this existing copper facility to transmit high speed data appears to be a more feasible choice towards the progress of the Primary rate ISDN. The advent of fiber in the distribution plant facilitates the availability of very high rate data ranging from 51.84 Mbit/s through 4.98 Gbit/s (SONET Rate) or Synchronous Optical Fiber Networks Rate at the network distribution centers. However, the use of fiber to every customer is not economical at this time.

The transmission of Basic Rate ISDN (BR-ISDN) with two B (bearer) channels at 64 kbit/s each and one D (delta) channel has already gained acceptance throughout US, Canada, Europe and Japan. The medium for transmission is consistent with the ISDN objective to deploy the twisted wire pair copper voice facility for the telephone services around the world. [1]

Such modulating techniques (QAM) are likely to enhance the data rates to T1 (1.544 Mb/s) used in USA, and to E1 (2.048 Mb/s) used in Europe in the subscriber loop plants. The feasibility of providing basic rate Integrated Services Digital Network (BR-ISDN) at 144 kb/s in the various telephone environments is well documented in [2] for the 2B1Q code.

A Convolutional codes are proposed in which the coder has a finite memory system, in contrast to the block coder, where it is a memoryless system. As the name implies, it refers to the fact that the added redundant bits are generated by modulo-two convolutions. For this type of code, we no longer consider individual blocks of bits as a codewords. Instead, a continuing stream of information bits is operated upon to form the coded message. The source generates a continuing message sequence of 1's and 0's, and the transmitted sequence is generated from this source sequence. The method to generate the transmitted sequence is to *convolve* the source with a fixed binary function. Therefore, a particular transmitted bit t_n is generated from the combination of source bits s_n, s_{n-1}, s_{n-2}, ..., s_{n-k} according to the convolution equation:

$$t_n = \sum_{k=-\infty}^{n} S_k h_{n-k} \qquad (1)$$

The h's in Equation (1) are either 1 or 0. This equation can be implemented with a shift register and a modulo-two adder.

Simple *trellis codes* consist of convolutional coders followed by line coders that represent the redundancy with a larger alphabet such as Quadrature Phase-Shift Keying (4-PSK), 8 Phase-Shift Keying (8-PSK), 16 Quadrature Amplitude-Shift Keying (16-QASK). Other examples are presented in [3].

2. CSA LOOP ENVIRONMENT

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 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].

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 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.

Moreover, 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 carrier serving area (CSA) loops have to meet the five following requirements:

enhance the data rates to T1 (1.544 Mb/s) used in USA, and to E1 (2.048 Mb/s) used in Europe in the subscriber loop plants. The feasibility of providing basic rate Integrated Services Digital Network (BR-ISDN) at 144 kb/s in the various telephone environments is well documented in [2] for the 2B1Q code.

A Convolutional codes are proposed in which the coder has a finite memory system, in contrast to the block coder, where it is a memoryless system. As the name implies, it refers to the fact that the added redundant bits are generated by modulo-two convolutions. For this type of code, we no longer consider individual blocks of bits as a codewords. Instead, a continuing stream of information bits is operated upon to form the coded message. The source generates a continuing message sequence of 1's and 0's, and the transmitted sequence is generated from this source sequence. The method to generate the transmitted sequence is to *convolve* the source with a fixed binary function. Therefore, a particular transmitted bit t_n is generated from the combination of source bits s_n, s_{n-1}, s_{n-2}, ..., s_{n-k} according to the convolution equation:

$$t_n = \sum_{k=-\infty}^{n} S_k h_{n-k} \qquad (1)$$

The h's in Equation (1) are either 1 or 0. This equation can be implemented with a shift register and a modulo-two adder.

Simple *trellis codes* consist of convolutional coders followed by line coders that represent the redundancy with a larger alphabet such as Quadrature Phase-Shift Keying (4-PSK), 8 Phase-Shift Keying (8-PSK), 16 Quadrature Amplitude-Shift Keying (16-QASK). Other examples are presented in [3].

2. CSA LOOP ENVIRONMENT

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 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].

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 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.

Moreover, 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 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].

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. By applying the carrier serving area design rules to this pseudo loop survey database, we have derived a Pseudo CSA (PCSA) database. Results derived from this database are presented in this paper.

The loop choice criteria imposed for the CSA loops curtails the 2290 loops (1983 loop survey) down to about 350 loops, thus eliminating about 85 percent of the loops.

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 [6].

3. SIMULATION ENVIRONMENT

3.1 *Specific Simulation Environment*

Simulation plays a major role. The number and the range of the secondary design parameters is too large for intuition or experience to cast a valuable insight. Computer-aided design (CAD) techniques do prevail and intelligent choices can be made by man-machine interaction [7]. Figure (1) illustrates the block diagram of the software organization for the simulation of the High speed Digital Subscriber Line (HDSL). Mass storage and database management techniques also become essential.

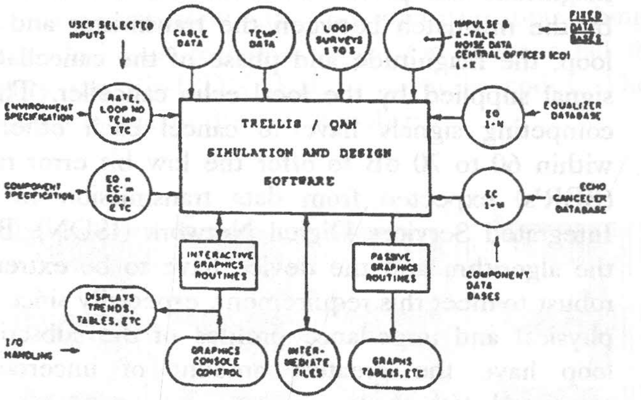

Figure 1. Block diagram of the simulation software.

Typical initial databases residing in the simulation facility would be the loop survey data, cable characteristics, temperature data of different geographical networks, urban suburban loop statistics, etc.

Primary derived databases would be physical and spectral domain characterizations, Fourier excitation functions at different bit rates, line codes, impulse noise characterization of different central offices, crosstalk data for the different cables and bundles, etc.

Secondary databases would be the time domain characterizations, scatter plots data, worst loop tabulations under different conditions, etc.

It became necessary to study the possiblity of using the Primary Rate ISDN (1.544 Mb/s), or referred to as T1 rate in the US, and E1 rate in Europe (2.048 Mb/s), along with the trellis coding techniques discussed, and apply this to the existing Carrier Serving Area (CSA) loop environment. The implementation of the trellis coding algorithm on the Carrier Serving Area (CSA) loop environment can be accomplished using a general purpose computer, with plotting capability. The Signal to Noise Ratio (SNR) plot is generated for the entire CSA database with different echo cancellations (i.e., 50 dB, 60 dB and 70 dB), and also to determine which loops fail to carry the T1 rate.

In the Adaptive Echo Cancellation (AEC) mode, the signal (transmit and receive) isolation occurs by two active devices (the electronic hybrid and the echo canceller), the success of the system is based upon a delicate dynamic balance between the magnitude and phase of the echo, as it is reflected by the mismatch between the transmitter and the loop, the magnitude and phase of the cancellation signal supplied by the local echo canceller. These competing signals have to cancel each other to within 60 to 70 dB to offer the low bit error rates (BER's) expected from data transmission in the Integrated Services Digital Network (ISDN). Both the algorithm and the device have to be extremly robust to meet this requirement, especially since the physical and impedance profiles of the subscriber loop have the greatest amount of uncertainty associated with them.

The software organization for the entire facility has been grouped into three parts:

a) The first part of the software deals with defining the system prior to the actual simulation.
b) The second part deals with the simulation per se. It generates numerical results from the input files in conjunction with the permanent databases that store the electrical characteristics of the system components, and of the twisted wire pairs carrying the QAM data. The intermediate results are stored for visual displays, or the files thus generated are reprocessed to extract statistically significant results from the simulation. Typical example of such a result is the fidelity of the transmission and the SNR in each of the 16-, or 64-point clusters of the QAM constellation.
c) The third part of the software deals with graphics and hard copy generation.

The second part (b) above of the simulation software depicted in Figure (1), is the most elaborate, since all numerical and computational algorithms are encoded here. An area of specific concern is the two dimensional (real and quadrature) components of cluster noise in the QAM/TRELLIS codes. The computational techniques for evaluating the SNR closely parallel the conventional techniques in any other signal processing environment for acoustic or video signals.

3.2 *The Database Management*

The manipulation of the primary, intermediate and the transitory databases needs special care. These databases become crucial to the actual computation and for the final graphic display.

(1) *Primary Databases*

The variety of these permanent database depends upon the extent and nature of the simulations. For a global PR-ISDN simulation, it will need the digital subscriber loop characteristics of all the different countries: the physical and electrical properties of the overall transmission media, the networking, and the carrier serving features, and so on. Generally, a localized or a national loop database suffices to initiate a limited study of the PR-ISDN environment. Topology of the loop plant, the primary and/or secondary electrical characteristics of the twisted wire pairs, the crosstalk and impulse noise databases generally constitute the primary databases for the PR-ISDN simulation.

(2) *Intermediate Databases*

Many intermediate files are necessary to conserve core space. An example of these write-read back files are files containing spectral components of excitation for each loop. The management of these files can be imposed upon the system user. With an extremely large number of files and updates, the system designer is faced with this additional task. Ideally, when the generated files are to be reprocessed for graphical display in the form of scatter plots, signal to noise ratio, etc., then the simulation facility provides built in safeguard to ascertain the accuracy of the displayed results. Effective file management is essential if the host computer system has limited disk space. In addition, long and recurring data files should generally be refreshed from the disk rather than by recomputation to reduce the execution time. Considerable precaution is necessary while using these databases. Lack of care in systematically deleting or over writing the data in these files, leads to over population of under utilized files. This is a serious situation in microcomputer environment due to limited disk space. On the other hand, a policy of successive overwrite may lead to loss of important data or sequence of steps.

(3) *Graphical Databases*

Simulation provides large amounts of significant results. These databases are reaccessed by the third part of the software to display the QAM clusters or to display the SNR's. Simple loop performance study needs little or no management of graphical databases. However, when the performance of all the loops in a typical loop database is to be evaluated, then a systematic strategy for the management of graphical databases becomes imperative.

Three steps are necessary to manage the display files:

First, the location of every one of the 8,192 QAM symbols in the constellation is tracked for any one loop.

Second, the integrity of the received symbols is verified against the transmitted symbols.

Third, if all symbols and their sequence is indeed intact, then the lowest SNR (in dB) for that loop is registered in an intermediate database at each of the 16 or 64 points of the constellation. The file containing the location of the 8,192 points is overwritten and reused when the next loop in the database is processed.

4. RESULTS

4.1 *Comparison of 16-QAM Trellis Coded (520 Kbauds) to the Uncoded 16-QAM (390 Kbauds)*

In the trellis coded 16-QAM scheme, 3 bits are directed to the convolutional encoder, becoming 4 bits at the encoder output, which are then applied to the line coder input for symbol transmission. The transmission rate is 514.67 Kbauds and approximated in the study to 520 Kbauds.

In the uncoded 16-QAM scheme, no convolutional encoder is being used. Therefore, 4 bits are input directly to the line coder. As a consequence, the transmission rate decreases to 386 Kbauds approximated in the present study to 390 Kbauds.

Figures (2) and (3) illustrate the SNR plots for the entire PCSA database (about 350 loops), using the trellis coded and uncoded 16-QAM schemes at 60 dB Echo Canceler (EC) for subscriber sides, respectively. The two figures are to be compared at the PR-ISDN data transmission. Trellis codes provide noise immunity and higher gain approaching the ideal gain for some loops. Other loops fail to carry the PR-ISDN data using trellis codes. The reason is due to the loop topology.

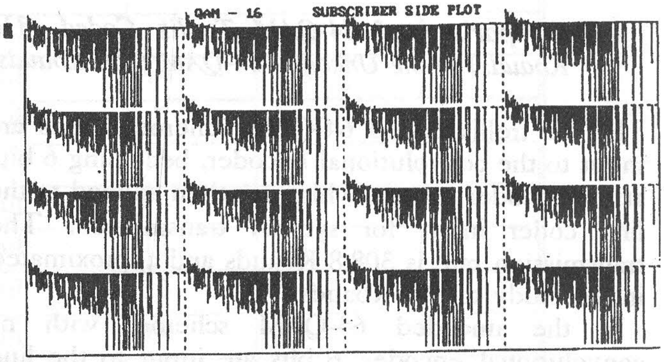

Figure 2. SNR's plotted as lines for each loop in every one of the 16 clusters at 60 dB EC (SUB side).

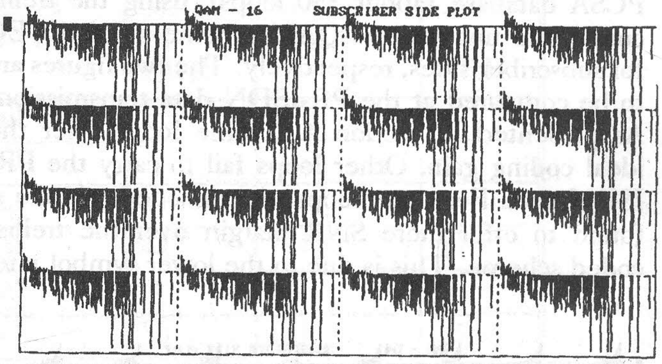

Figure 3. SNR's plotted as lines for each loop in every one of the 16 clusters at 60 dB EC (uncoded SUB side).

The uncoded scheme carries the data for some of the loops that failed the PR transmission using trellis coded scheme. The reason for this result is due to the lower symbol rate. The loop configuration has a tremendous effect on the ability of a loop to carry coded or uncoded data. The length of the loop, and of Bridged Taps (BT's), the number and total length of BT's, and the location of each BT with respect to the subscriber side, each has its individual effect. These factors govern the quality of transmission in any loop environment.

In summary, at 60 dB EC, with uncoded 16-QAM, 6 loops (1.7% of the PCSA loops) failed to carry the PR-ISDN data, compared to 13 loops (3.7% of PCSA loops) in the coded 16-QAM scheme. Table (1) presents the details and topologies of loops unable to carry the PR-ISDN data for the coded and uncoded 16-QAM schemes.

4.2 *Comparison of 64-QAM Trellis Coded (310 Kbauds) to the Uncoded 64-QAM (260 Kbauds)*

In the trellis coded 64-QAM scheme, 5 bits are input to the convolutional encoder, becoming 6 bits at the encoder output, which are then applied to the line coder input for symbol transmission. The transmission rate is 308.8 Kbauds and approximated in the study to 310 Kbauds.

In the uncoded 64-QAM scheme, with no convolutional encoder, 6 bits are input to the line coder. The symbol rate decreases to 257.33 Kbauds which is approximated in the study to 260 Kbauds. Figures (4) and (5) illustrate the SNR for the entire PCSA database (about 350 loops), using the trellis coded and uncoded 64-QAM scheme at 60 dB EC for subscriber sides, respectively. The two figures are to be compared at the PR-ISDN data transmission. As presented in section 4.1, some loops offer the ideal coding gain. Other loops fail to carry the PR-ISDN data. For some loops, the uncoded scheme is found to offer more SNR margin over the trellis-coded scheme. This is due to the lower symbol rate.

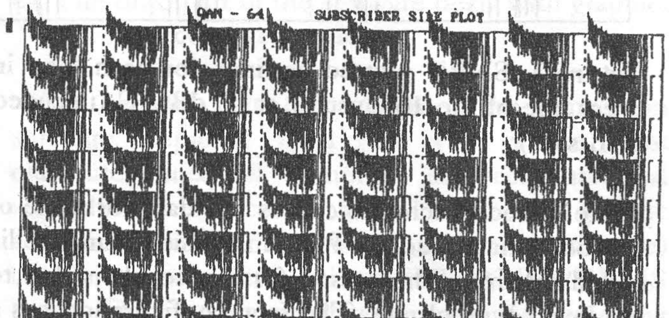

Figure 4. SNR's plotted as lines for each loop in every one of the 64 clusters at 60 dB EC (SUB side).

The trellis-coded 64-QAM scheme has fewer (7 vs. 13) loop failures than the trellis-coded 16-QAM scheme (see Table 1 and 2). When coded 64-QAM is compared to the uncoded 64-QAM, the loop topology influences its performance.

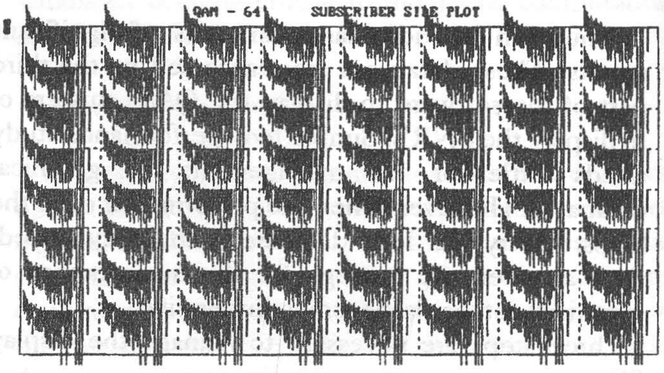

Figure 5. SNR's plooted as lines for each loop in every one of the 64 clusters at 60 dB EC (uncoded SUB side).

In summary, at 60 dB EC, with uncoded 64-QAM, 5 loops (1.4% of the PCSA loops) failed to carry the PR-ISDN data, compared to 7 loops (2% of PCSA loops) in the coded 64-QAM scheme. Table (2) presents the details and topologies of loops unable to carry the PR-ISDN data for the coded and uncoded 64-QAM schemes.

5. CONCLUSION

This paper discusses and compares the performance of the trellis-coded 16-QAM scheme (520 Kbauds, i.e., 3 information bits per symbol) with the uncoded 16-QAM scheme (390 Kbauds, i.e., 4 information bits per symbol). This comparison is accomplished using a typical Carrier Serving Area loop environment.

The 16- and 64-QAM Signal to Noise Ratio (SNR) constellations have been presented throughout this study. The response of the typical CSA loop environment has also been presented.

A comparison between the coded and uncoded schemes for the two constellations (i.e., 16-QAM and 64-QAM) at 60 dB EC is presented. It is noticed that the trellis-coded schemes work well with some loops and fail with others due to the loop topology and the critical locations of BT's. The uncoded schemes are also influenced by the same factor, providing a lower failure rate with 16- and 64-QAM clusters.

Table 1. Loops falied to carry PR-ISDN in 16-OAM at 60 dB EC.

LP#	SEC	BT	BT LEN ft	LP LEN ft	COD 16-QAM	CLUS IN ERR	UNC 16-QAM	CLUS IN ERR
3	4	2	1158	6964	fail	8	fail	12
18	2	1	234	7390	fail	8	pass	--
22	2	1	340	8347	fail	15	fail	10
40	4	2	443	7562	fail	9	pass	--
53	5	2	557	6022	fail	13	pass	--
119	2	1	241	8107	fail	16	pass	--
129	2	1	120	8857	fail	7	pass	--
131	4	2	988	7800	fail	16	fail	16
186	3	1	905	10642	fail	16	fail	15
239	2	1	325	10032	fail	13	fail	6
301	4	2	1229	7286	fail	13	pass	--
331	2	1	323	6587	fail	14	pass	--
350	4	2	1746	8626	fail	7	fail	2

TABLE 2. loops failed to carry PR-ISDN in 64-QAM At 60 dB EC.

LP#	SEC	BT	BT LEN ft	LP LEN ft	COD 64-QAM	CLUS IN ERR	UNC 64-QAM	CLUS IN ERR
3	4	2	1158	6964	fail	61	fail	60
103	4	2	1173	5683	fail	6	pass	--
131	4	2	988	7800	fail	61	fail	5
186	3	1	905	10642	fail	62	fail	63
209	3	1	800	9464	fail	4	fail	2
257	3	1	608	10164	fail	58	fail	33
265	4	1	515	7493	fail	44	pass	--

The symbol rate also affects the loop failure. The symbol rate for the coded 16-QAM scheme (520 Kbauds) is 25% more than that of the uncoded 16-QAM scheme (390 Kbauds). The loop failure rate is 13 versus 6, respectively, for the typical loops in the PCSA loop database.

The symbol rate for the coded 64-QAM scheme (310 Kbauds) is about 17% more than that of the uncoded 64-QAM scheme (260 Kbauds). The loop failure rate is 7 versus 5, respectively, for the loops in the PCSA loop database.

The reason for the increased loop failure arising in the trellis-coded system is also due to the increase of residual reflected signals at higher rates with enhanced equalization, as well as the attenuation of the signal level. These two reasons together do not compensate for the trellis gain of the coded system.

In conclusion, the noise advantage of the trellis codes needs to be critically evaluated for the particular loop environment. The practical limitations of the system components and transmission media can prevent the complete realization of the ideal noise advantage of these coding algorithms.

REFERENCES

[1] S.V. Ahamed, "Simulation Results for QAM Codes for DS-1 Rate in Subscriber Loop Plant," l1991 International Simposium on Circuits and Systems, pp. 2741-2744.

[2] J.W. Lechleider, "Line Codes for Digital Subscriber Lines," *IEEE Communications Magazine*, vol. 27, No. 9, September, 1989.

[3] E.A. Lee and D.G. Messerschmitt, *Digital Communication*, Kluwer Academic Publishers, Boston, MA, 1988.

[4] M.J. Miller and S.V. Ahamed, *Digital Transmission Systems and Networks, Applications*, vol. II, Computer Science Press, 1987.

[5] T.P. Byrne et al., "Positioning the Subscriber Loop Network for Digital Services," *IEEE Trans. Commun.*, vol. COM-30, No. 9, September 1982.

[6] G.S. Moschytz, S.V. Ahamed, "Transhybrid Loss with RC Balance Circuits for High Speed Full Duplex Modems," *IEEE Journal on Selected Areas in Communications*, vol.SAC-9, No.6 pp. 951-959, August 1991.

[7] S.V. Ahamed, "Simulation Environments for High Speed Digital Subscriber Line (HDSL)," in Conf. Rec. ICC'93, Geneva, Switzerland, May 23-26, 1993, vol. 3, pp. 1791- 1796.

[8] E. Biglieri, D. Divsalar, P.J. McLane and M.K. Simon, *Introduction to Trellis-Coded Modulation with Applications*, Macmillan Publishing Company, New York, 1991.