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COMMUNICATION THEORY AND THE DATA COMMUNICATION RESEARCH PROGRAM

by

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I. Introduction

The following material is prepared as an outline of the technical areas of importance to IBM Corporation in data transmission.

In analyzing the technical problems of data transmission it is important to review the physical limitations on channel capacity, for example, as stated by Shannon, [1] and the correlation of signal and noise waveforms as developed by Wiener[2], to determine how close to the theoretical limits present and proposed systems come. Learning where we are in respect to fundamental physical limits should help point to directions in which solutions to data transmission problems must be sought.

Most present data transmission systems operate near 16% of theoretical channel capacity. It is constructive to know that simply increasing the bit rate results in poorer separability of noise and signal by Wiener filtering on account of impulse noise and signal waveforms approaching each other in wave shape and spectrum.

These problems have been outlined in Figure E-1 on levels of organization similar to the way some sociologists[3] and biologists[4] classify the subdivisions of their field of study and the relationship of their work to other fields. The rows are arranged with the most basic physical level at the bottom in such a way that each level is dependent upon the levels below it. The vertical columns are arranged in approximate order from left to right of determining needs, interpreting basic science, general engineering development, and special projects. The areas that are filled in are not necessarily complete. They represent the areas known to the author to be topics of analysis in the recent past, present, or scheduled for the near future. The author would appreciate receiving corrections and additions to the list.

The level described as "information networks" deals with the alternative ways different points in a communication system can be connected. The problems of describing and analyzing different group structures, including hierarchies with communication between links at intermediate levels have been formulated by A. Bavelas.[5] A set of theorems have been developed by M. Kochen[6] for the analysis of several simple classes of communication networks such as open chains, closed chains, stars, and simple hierarchies.

It is expected that Product Planning can through their contact with the real business world supply advice as to which types of networks are realizable in business.

II. Efficiency and Queuing

The overall systems requirements established for particular projects require sharing of components of a communication network by various types of multiplexing. A system designed for low cost and efficient use of components will have queuing problems during peak usage times. Erlang, Grinsted, Lely, Lubberger, Molina and others have applied probability theory to telephone trunking.[7-9] More general theories of telephone traffic have been developed in Holland and Sweden.[10]

Consideration of the available analyses has shown that different conditions exist in the data transmission multiplexing problems considered in San Jose Research such as uniform message length, inclusion of sender identification with each transmission, and the use of an assembly buffer storage memory. For these conditions, N. M. Abramson has developed an analysis of the queuing problem.[11] As new systems of communication are proposed, the conditions must be analyzed to see what further queuing analyses are required.

III. Message Organization and Block Length

This area deals with the comparison of using redundancy for error-correction in contrast to using less redundancy with a feedback signal for repeating of blocks in error. Bishop and Buchanan have proven a theorem that redundancy for error-correction is more economical than using feed-back to request a repeat when an error occurs.[12] These mathematical-physical conclusions apply to certain parts of the data transmission problem such as the remote keying of data into an assembly buffer.

For other conditions such as the transmission of complete messages into a central computer the value or "risk" associated with unusual error events may require feedback to prevent loss of data when these unusual events occur. Under such conditions the problem is to determine the optimum ratio of redundancy and feedback. A large segment of this area has been analyzed at San Jose.[13] Some related analyses have been made at Poughkeepsie.[14] These analyses compare existing codes of the Hamming type. Since the feedback loop does not increase the channel capacity, there is a possibility that a new code could be developed to provide both the feedback and an increase in channel capacity. This part of the problem is being investigated at the Lamb Estate.

A group at New York University using operations research methods has made a comparison of information feedback and decision feedback.[15] Our analyses at San Jose corresponds to their decision feedback. A more general consideration of the application of this work to IBM data transmission problems is desirable.

IV. Character Organization (Coding)

Here the requirements of coding studies differ in different divisions of IBM. Codes developed for particular computers or data transmission channels are not necessarily the best for new applications. The objective in San Jose is to use codes developed elsewhere if applicable. The work of Dr. A. B. Fontaine (Lamb Estate) and Mr. J. E. MacDonald (Poughkeepsie) has provided a map of known codes derived from Hamming's basic error-correcting code.[16-19] Examination of the OMNICODE[20] developed in Poughkeepsie shows it to be generally useful in simplifying the conversion between different codes and in simplifying the logical circuit hardware to certain modular units. This OMNICODE provides different levels of error-detecting and error-correcting for computing circuits and data transmission circuits.

For character by character transmission with station identification, twelve information bits are required which make the OMNICODE system inefficient for double error-correcting. Many of the other analyses available are for independent errors. The nature of impulse noise on telephone lines increases the probability of double adjacent errors which means the errors are non-independent. A double error-correcting code of less redundancy than the Hamming codes would be sufficient for this case. N. M. Abramson[21] has developed some theorems for the derivation of single-error-correction, double-adjacent-error-correction (SEC-DAEC) codes.[21] It is probable that a graduate student at Stanford University will work on the problem of triple-adjacent-error-correcting codes. The development of certain particular SEC-DAEC codes may be suitable for using 704 programs such as have been developed at the Lamb Estate for code evaluation.

Since most known coding studies are for independent symmetric channels, studies have been made in San Jose for certain elementary codes such as 4-out-of-8, six and seven bit codes with longitudinal block checks for a range dependent errors.[22A] Other types of block checking have been analyzed by R. M. Gryb.[22B] Studies of m-out-of-8 codes, one and two dimensional parity checking, and probabilities of undetected errors for various codes have been made in Endicott.[23] Some comparisons have been made between the 4-out-of-8 code and other elementary codes for non-symmetric channels in San Jose[24] and Endicott.[23]

Special Engineering Products Division has prepared curves of the probability of undetected errors as a function of bit error probability for examples of SED, Hamming SEC-DED, Slepian DEC-TED, and Huffman linear delay codes.[25] These studies are for symmetric independent channels. The preliminary data on error distribution on telephone circuits indicates that unsymmetric non-independent channels are likely to be encountered in practice.

Bell Telephone Laboratories have developed burst-correction codes which should be evaluated in respect to our problems.[26] Since they are designed for dealing with bursts of dependent errors.

Some work at Poughkeepsie has lead to some important theorems on the existance of closed-packed or perfect codes of which the Golay code is one case.[27A]

V. Channel Capacity

The basic theorem on channel capacity has been given by Shannon:[1]

$$C = W \log_2 (1 + S/N),$$

where C is the channel capacity (bits/sec), W is the bandwidth (cycles/sec), and S/N is the signal-to-noise ratio for gaussian white noise. Sunde[28] has added a distortion factor which modifies the channel capacity due to delay distortion. The existing formulas for channel capacity require more data on the nature of the noise wave shape and distribution in time. The S/N term applies to gaussian white noise. A more general definition of the signal-to-noise ratio is needed for use with other noise distributions.

Before attempting a rigorous derivation of the effect of impulse noise on channel capacity, it is planned to work out a graphical method of obtaining an upper bound on the error probability of impulse noise from which an upper bound to the channel capacity as function of impulse noise parameters can be constructed.

The few special cases in the literature where the channel capacity formula is known for non-gaussian noise distributions are referred to in Section VII, Modulation Systems. Studies of information theory in the

Soviet Union are becoming more important to us. P. E. Green of M.I.T. Lincoln Laboratory has maintained a periodic review of the state of information theory in the U.S.S.R.[27B - 27C]

VI. Signal Bit Structure (Waveform)

Whether filtering or logic is used to distinguish between signal and noise, careful attention must be paid to the waveform selected for the signal. The choise is dependent upon both the noise distribution and the modulation system.

Sunde[29] suggested a "dipulse" waveform. E. Hopner and H. G. Markey[30-3] developed a practical data transmission system using dipulses. N. M. Abramson analyzed the interbit interference of different dipulse waveforms.[32] Possibilities of other waveforms have been discussed by R. Filipowsky of Westinghouse,[33-34]

These recent developments are for data transmission on voice channels of three kilocycles bandwidth. As larger bandwidth channels are utilized for higher bit rates, other wave shapes may have to be considered. The experience of Watson Laboratory with multimicrosecond pulses and microwave logic may help IBM deal with problems of these higher bit rates.

VII. Modulation and Demodulation System

A. Theoretical Analyses

The papers given by Z. Jelonek[35] and Stanford Goldman[36] at the 1952 London Symposium on Communication Theory plus the published discussion of their papers constitute a thorough coverage of the known systems. Recent papers on the Collins Kineplex[37] system and the work of J. P. Costas[38-3] on synchronous detection should be added to bring the analyses up to date. Goldman discusses the curves of receiver signal-to-noise ratio versus distance in radio communication using AM (ssb), AM (dsb), FM (wb) and PWM (vws). Jelonek has developed formulas for the channel capacity for a large group of possible modulation systems including AM, PAM, PAM-AM, PCM-d.c. and AM, FM, PPM, PDM, etc. The discussion of his paper fills in gaps in the possible modulation systems such as AM transmit with PM receiver.

Systems IBM is working with need to be analyzed on an equivalent basis for comparison with the above mentioned modulation systems. Most of these comparisons require either the probability of error or the channel capacity. Existing analyses usually are in terms of gaussian white noise (thermal). It may be necessary to go through the work of Jelónek with impulse noise to see if the comparisons come out differently for different noise distributions.

Recent articles in Russian scientific and engineering journals compare different modulation systems under different conditions.[40] Understanding of Siforov's[41] analysis of a Rayleigh fading noise model and his proposals for obtaining infinite channel capacity is important. Recent work in the USSR[42] has produced an interesting model of gaussian fading distribution. We need to develop an understanding of these theoretical models and prepare simplified explanations to help our engineers utilize these theories.

B. Customer Owned Channels

Some work has been done on intra-plant cables to calculate from physical dimensions and constants the primary cable constants.[43] From these, the attenuation, phase, and bandwidth (a function of length) can be calculated. From the bandwidth the channel capacity of cables can be calculated. A set of these calculations are in process in San Jose.

Other types of customer owned channels such as microwave links' need to be examined. If the customer has a microwave link voice communication network, such as the pipe lines, oil companies, and public utilities have, the compatibility of voice and data transmission is a problem in regard to fading. An intermediate size system may be able to operate a microwave link more economically than leasing lines, but cannot afford alternate channels with automatic switching. This may require an alternate code that is more redundant for use under heavy fading conditions or it may require an adjustable block length answer back system.

C. Public Utility Channels Using Voice Telephone System

This area requires periodic conferences with the telephone companies. It could be handled as an AIEE or International Committee function.

1. Present Systems

IBM must keep up with the status of communication practice to insure that compatible data transmission systems are available. At present there are physical types of circuits which must be avoided on account of synchronization troubles. On microwave links the switching to alternate channels can cause errors. On transoceanic data transmission special radio channels without voice scramblers or cable circuits have to be used if excessive repeating of blocks is to be avoided. There are questions as to whether shorter block length, a different synchronization system should be used, or can simple changes be made in the voice scramblers.

2. Future Systems

The telephone companies are considering new systems such as: Pulse Code Modulation for voice transmission and a Time Assignment and Speech Interpolation for transoceanic cable voice transmission.[44] Compatible data transmission systems must be undertaken to fit possible future communication systems so that customers who use dial-up service for data can continue to have the type of service after telephone plant charges are made.

VIII. Develop Understanding of Noise Sources

A. Theoretical Models of Noise Sources

1. Gaussian Thermal Noise

This source of noise is well known, both theoretically and experimentally. There are over six hundred articles in the literature on noise,[45] of which a majority of articles are on gaussian noise. The problem here to determine which specific analyses have bearing on our work. For example the filtering of high level gaussian noise with a narrow band filter results in a Rayleigh distribution, which then needs evaluation. Another use of the review of the well know gaussian noise is to develop simplified representations which might lead to better models of other types of noise.

2. Impulse Noise

Develop theoretical model based on assuming a physical distribution of pulses on a physical distribution of cable pairs.

3. Crosstalk Noise

A part of the coupling problem for Impulse Noise.

There are four stages or levels of crosstalk to be evaluated:

a. Coupling between parallel cylindrical pairs of wires. (A straightforward classical problem.)

b. Coupling between twisted pairs. This may require an experimental measure of the lack of symmetry of the twisted pairs in manufactured cables. Some experimental data is available on coupling between cable pairs.[46]

c. Coupling between balanced pairs in telephone cables. It is the practice in telephone work to balance the pairs to further reduce the crosstalk.

d. Additional reduction of crosstalk coupling due to particular modulation system such as the compandors in N-carriers.

4. Fading on Microwave Links.

Data on attenuation due to fading and how the telephone systems deal with it[47] is available. The voice channels on microwave channels are switched to alternate routes automatically when fading or repeater failure reaches a certain level. The attenuation to this switch-over level does not impair data transmission, but the loss of synchronization on switching causes data error. The problem is one of compatibility of the switching level for voice and for data transmission.

B. Experimental Data on Noise

We have a tape recording of impulse noise for one N-carrier channel. MIT Lincoln Laboratory has collected error data on some circuits. More samples are needed. San Jose Research and/or Kingston MPD could collect and analyze data on impulse on additional circuits. It is assumed that only a sampling is necessary to be done by IBM, since Bell Telephone Laboratories is assumed to be conducting more extensive studies.

There is sufficient data in the literature on thermal noise, crosstalk and fading to give us approximate limits for these noise sources. Preliminary analysis at San Jose shows that the different types of noise can be grouped into classes of noise by the number of parameters required to make approximate upper bounds for their probability curves.

C. Fine Structure of Noise

Since impulse noise is capable of causing multiple (within the same character) and adjacent errors, both theoretical and experimental studies of the noise waveforms are needed to determine the probability of multiple errors.

IX. Physical Parameters of Channels

The use of classical formulas for primary cable constants has been checked.[43] The analysis is in terms of the frequency variation of the R, L, G, and C, from which other representations can be constructed. Some work of the Zurich Laboratory has analyzed the influence of the skin effect on the transient response in single conductor.[48]

Attenuation and ~~xxxx~~ phase characteristics of one telephone channel were measured at San Jose. Data on other voice channels have been obtained from Bell System reports.

X. Conclusions

These questions require the circulation of lists of this nature to the different Research and Product Development Laboratories for discussion so that the best coverage of these problems can be obtained to keep IBM on the frontier of knowledge and technique of data transmission. This material might serve as possible agenda for a future meeting of the data transmission committee (engineering liaison). The checking chart of Figure E-1 can be used to check the completeness of coverage by this area in protecting the future requirements of IBM Corporation.

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