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THESIS

AN ANALYSIS OF FOUR ERROR DETECTION AND CORRECTION SCHEMES FOR THE PROPOSED FEDERAL STANDARD 1024 (LAND MOBILE RADIO)

by

Carol A. Lohrmann

March 1990

Thesis Advisor T. A. Schwendtner

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Interoperability of commercial Land Mobile Radios (LMR) and the military's tactical LMR is highly desirable if the U.S. government is to respond effectively in a national emergency or in a joint military operation. This ability to talk securely and immediately across agency and military service boundaries is often overlooked. One way to ensure interoperability is to develop and promote federal communications standards (FS).

This thesis surveys one area of the proposed FS 1024 for LMRs: namely, the error detection and correction (EDAC) of the message indicator (MI) bits used for cryptographic synchronization. Several EDAC codes are examined (Hamming, Quadratic Residue, hard decision Golay and soft decision Golay), tested on three FORTRAN programmed channel simulations (INMARSAT, Gaussian and constant burst width), compared and analyzed (based on bit error rates and percent of error-free superframe runs) so that a "best" code can be recommended. Out of the four codes under study, the *soft decision* Golay code (24,12) is evaluated to be the best. This finding is based on the code's ability to detect and correct errors as well as the relative ease of implementation of the algorithm.

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An Analysis of Four Error Detection and Correction Schemes for the proposed Federal Standard 1024 (Land Mobile Radio)

by

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Submitted in partial fulfillment of the requirements for the degree of

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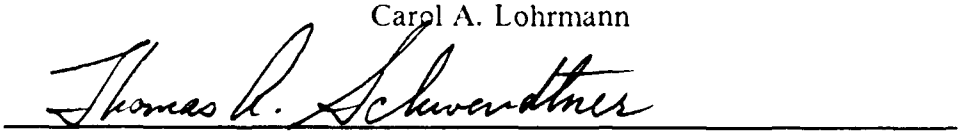
Approved by: 

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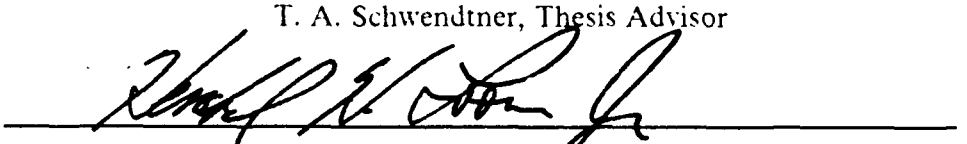

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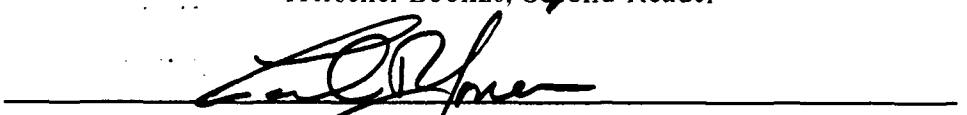

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ABSTRACT

Interoperability of commercial Land Mobile Radios (LMR) and the military's tactical LMR is highly desirable if the U.S. government is to respond effectively in a national emergency or in a joint military operation. This ability to talk securely and immediately across agency and military service boundaries is often overlooked. One way to ensure interoperability is to develop and promote federal communications standards (FS).

This thesis surveys one area of the proposed FS 1024 for LMRs; namely, the error detection and correction (EDAC) of the message indicator (MI) bits used for cryptographic synchronization. Several EDAC codes are examined (Hamming, Quadratic Residue, hard decision Golay and soft decision Golay), tested on three FORTRAN programmed channel simulations (INMARSAT, Gaussian and constant burst width), compared and analyzed (based on bit error rates and percent of error-free superframe runs) so that a "best" code can be recommended. Out of the four codes under study, the *soft decision* Golay code (24,12) is evaluated to be the best. This finding is based on the code's ability to detect and correct errors as well as the relative ease of implementation of the algorithm.

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THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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LIST OF ACRONYMS AND ABBREVIATIONS

APCO	Association of Public Safety Commission Officers
AWGN	Additive White Gaussian Noise
A/D	analog to digital modulation (usually infers D/A)
BER	bit error rate
C3	Command Control and Communications
CELP	Codebook Excited Linear Predictive Coding
COMSEC	Communications Security
dB	decibels (relative unit of measure, usually for noise)
DCA	Defense Communications Agency
DIRNSA	Director of NSA
DOJ	Department of Justice
DSP	Digital Signal Processing
EDAC	Error Detection and Correction
FM	Frequency Modulation
FS	Federal Standard
FSK	Frequency Shift Keying
FTSC	Federal Telecommunications Standards Council
IC	Integrated Circuit
ICASSP	International Conference on Acoustics, Speech and Signal Processing
ICEP	INMARSAT Codec Evaluation Proposal
INMARSAT	International Maritime Satellite
LMR	Land Mobile Radio
lsb	least significant bit
MI	Message Indicator
msb	most significant bit
NCS	National Communications System
NSA	National Security Agency

NSEP	National Security Emergency Plan
PDF	Probability Distribution Function
OOS	Out-of-Synchronization
QDPSK	Quadrature Differential Phase Shift Keying
QRC	Quadratic Residue Code
PN	Pseudorandom Noise
RF	Radio Frequency
S/N	Signal to Noise Ratio (usually measured in dB)

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I. INTRODUCTION

A. BACKGROUND

1. Why Land Mobile Radio Standards are Needed

Interoperability, connectivity and security of the U.S. land mobile radio (LMR) communications systems are important objectives at all levels - federal, state, and local. In many ways the U.S. falls short in meeting these communications objectives. "This situation is even more serious when viewed in the National Security Emergency Preparedness (NSEP) context"[Ref. 1]. During such an emergency, private users of a land mobile public safety system may need to communicate with federal defense and law enforcement agencies to effectively execute emergency operations. This is not currently possible.

Within the defense community, interoperability between various services is a longstanding problem. An example that illustrates the extent of this problem is provided by the communication problems encountered during the Grenada conflict. Many rumors have circulated about a soldier who used his AT&T card to call back to the continental United States by phone, since he could not communicate with soldiers on the other side of the island due to lack of radio interoperability.[1] For all future joint military conflicts, interoperability between the services is a necessity.

The absence of a federal communications standard for the LMR, until most recently, has encouraged the proliferation of a diverse group of technically incompatible LMRs. The fact that the commercial market has produced a wide variety of state-of-the-art equipment is good in one sense -- there is much to choose from and the competition in the commercial market place keeps the cost low. However, each manufacturer produces his own "best" product with no standards or guidelines to follow. Modulation schemes, for example, may be different. This makes communication possible only with someone who has pur-

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1 This story has never been substantiated.

chased a radio from the same vendor. But if the overall objective is to promote LMR interoperability across agency and service boundaries, then more thorough standardization is necessary.

2. Current and Proposed LMR Standards.

There is presently a LMR standard in place -- Federal Standard (FS) 1023. Because of it's late adoption (September 1989), it did not have an impact on existing defense or civilian LMR systems; many incompatible LMRs were already fielded. FS 1023's near-term objective was to prevent further proliferation of incompatible systems until a new standard for future upgraded systems could be agreed upon.

FS 1023 will be obsolete in the near future, in part because "...increasing demands on the fixed spectrum availability along with overseas evolution towards narrower channels have caused the need for efficient spectrum use." [Ref. 2] Today, new technological advancements enable more efficient use of the frequency spectrum. FS 1023 is based on 25 kHz allocated channel spacing; the proposed standard, FS 1024, will require a narrower allocation of frequency channel spacing -- 12.5 or 6.25 kHz.

LMR interoperability, through the adoption of FS 1024, is an achievable mid-term goal. Such an LMR standard would help to alleviate both interoperability and spectral congestion concerns.

Because of the interest and justifed need for a future federal standard, the National Communications System (NCS) office of Technology and Standards, the National Security Agency (NSA) and the Land Mobile Radio (LMR) subcommittee of the Federal Telecommunication Standards Committee (FTSC) are working together to develop Federal Standard 1024 to meet the future needs of all LMR users -- federal (civil and defense), state, and local. The official draft FS 1024 is expected to be released in Spring 1990 for 90 day industry coordination and comment [Ref. 3]. Other correspondents involved include the U.S. Department of Justice (DOJ), the Assistant Secretary of Defense for C3I, and the General Electric Company [Refs. 1, 4, 5, 6, 7, 8, and 9].

3. Advantages and Disadvantages of FS 1024

There are three clear advantages with the adoption of FS 1024. First, full and open competition between commercial LMR vendors will become healthier. Clearly the company with the best product for the money will win a competitive procurement. Second, a healthy market will produce a greater availability of LMR products. Third, it is likely that the standard will extend beyond the bounds of the intended commercial LMR market to the tactical defense radio market. This "status quo" effect, driven by the adoption of FS 1024, would have a positive influence on intra-service communications compatibility and interoperability.

Most often, each service provides the communications for its own units. There is a wide variety of tactical radios fielded for dozens of unique applications. It is more of an exception when these radios are able to interoperate. FS 1024 may be seen, then, as a first step in enhancing cross-service interoperability requirements for tactical (land mobile) units.

The main disadvantage of FS 1024 is that standardized radios would not be backwards compatible with existing radios that comply with FS 1023. An upgrading of all existing systems, a high-cost and highly unlikely proposition, would be necessary before full interoperability could be obtained. Over time this disadvantage will be lessened since an in-place Federal Standard for new LMR systems will ultimately drive the replacement of existing systems.

B. DESCRIPTION OF LAND MOBILE RADIO FS 1024

The narrowband digital LMR standard includes three criteria to ensure interoperability. These three criteria are:

- voice coding (digitization) technique,
- the radio frequency (RF) modulation technique,
- the cryptographic algorithm and cryptographic synchronization.

The voice coding techniqe refers to another federal standard - FS 1016.[2] This standard specifies CELP (codebook excited linear predictive) coding as the requirement. CELP coding will be implemented with a 8 KHz sampling rate. The algorithm itself contains three functions: short term spectral prediction, long delay adaptive codebook "pitch" searches, and innovative stochastic codebook search.

The second criterion, RF modulation, is still under consideration. Possibilities include 4-ary frequency shift keying (FSK), tamed frequency modulation (FM), quadrature differential phase shift keying (QDPSK) and $\pi/4$ shift QDPSK.[3] Final selection will be based on spectral efficiency (minimizing adjacent channel interference) and power efficiency.

C. SCOPE AND GOAL OF THESIS STUDY

The third criterion, cryptographic algorithm and sychronization is the portion of FS 1024 on which this thesis will concentrate. The focus is on the error detection and correction (EDAC) scheme for the message indicator (MI) portion of the synchronization bits, within the allocated transmission format.

The goal of this study is to determine the most suitable EDAC code, among four -- Hamming, Quadratic Residue Code (QRC), Golay hard decision and Golay soft decision -- for cryptographically securable LMRs. Factors affecting the findings are also discussed. Analyses and findings are based on a computer simulation. The thesis only addresses block codes. Convolutional codes were eliminated from consideration by DIRNSA based on a study by NASA [Ref. 11]. Longer processing delays -- characteristic of convolutional codes -- are considered unacceptable for use in LMR, where a more immediate response is required.

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2 FS 1016 is proceeding through the FTSC approval process [Ref. 10: p. 3] and is expected to be approved by the Summer of 1990.

3 In an analysis performed by NSA, coherent and mainly noncoherent $\pi/4$ shift QDPSK were used. [Ref. 2]

D. ORGANIZATION OF THESIS

Chapter II discusses the transmission frame (bit) structure and proposed interleaving scheme. Interleaving and EDAC serve to mitigate noise induced errors.

Chapter III discusses and describes the EDAC codes considered.

Chapter IV describes the simulation and tests performed.

Chapter V presents the test results.

Chapter VI provides conclusions and recommendations for further study.

The appendix contains the FORTRAN code for the computer simulations used (Appendix A), the selected output data of the simulation runs (Appendix B), and the codeword interleave tables for each code type (Appendix C). Golay hard and soft decision use the same interleave table, therefore, there are only three algorithm 'types' out of the four codes tested.

E. THESIS COLLABORATION AND SUPPORT

This thesis was performed in consonance with DIRNSA R556 as an aid in their study and analysis of the FS 1024 issues for DIRNSA V2 (secure voice acquisition) and the National Communications System (NCS). Also, GTE Government Systems Corporation - Electronic Defense Communications Division in Waltham, Massachusetts is currently evaluating portions of the new FS 1024 for DIRNSA under contract number MSA904-90-C-6014.

II. TRANSMISSION FRAME STRUCTURE AND INTERLEAVING

A. FS 1024 SUPERFRAME AND FRAME

Figure 1 on page 7 shows the bit allocation for the FS 1024 data rate of 8000 bits/s. Table 1 on page 8 summarizes bit allocation and the respective bit rate for each superframe. For each second, 2400 are Error Detection and Correction (EDAC, or "parity") for the information bits, 4800 of the bits are information bits (CELP processed) and the remaining 800 bits are used for overhead processing. Bits allocated for overhead processing include bits for:

- framing
- mode control
- system control
- cryptographic synchronization (i.e., message indicator (MI) bits)

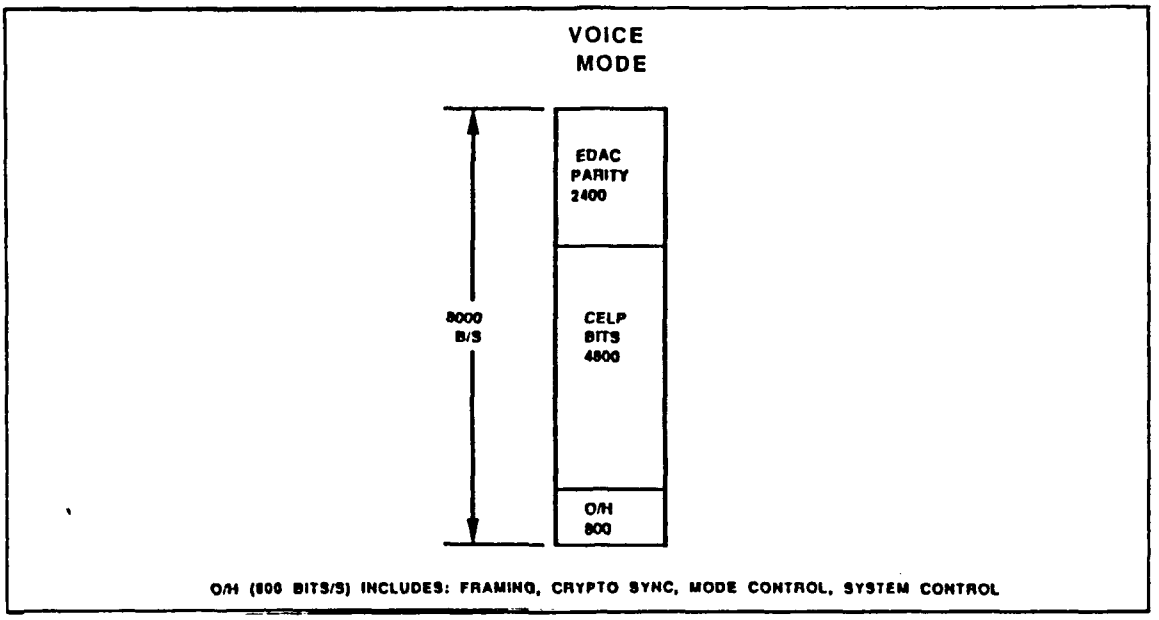

Figure 1. Data Rate Allocation (Source: GTE Government Systems Corp., LMR program review, Waltham, MA)

Table 1. SUPERFRAME BIT COUNT (420 MS)

	Bits SF	Bits s
Voice EDAC (parity)	1008	2400.00
Voice (CELP bits)	2016	4800.00
Framing	48	114.28
Mode Control (MC)	4	9.52
MC EDAC	10	23.80
Msg Indicator (MI)	72	171.42
MI EDAC	72	171.42
Reserved bits	6	14.29
System Control	124	295.24
Total	3360	8000

Adapted from GTE - Government Systems Corporation

For the recommended superframe transmission and interleaving format, there are 8 modes of operation defined by 4 bits in the 800-bit overhead control field: four are for the encrypted mode and four for the plain text mode. Only the encrypted voice mode, designated as 0100 in the mode control block, will be addressed in this thesis since the message indicator (MI) bits are not used in the unencrypted or plain text frame structure.

Figure 2 on page 9 shows the proposed frame structure for both the encrypted and the plain text mode. The shaded portion, the information superframes, is the only section of the message considered. The plain text mode does not incorporate EDAC or MI bits; thus, plain text superframes are half the duration.

Figure 3 on page 10 provides a one second snapshot of 8000 bits. Each superframe contains fourteen 30 msec frames. A total of 72 MI bits plus 72 MI parity bits will be interleaved throughout these 9 of these 14 frames, in a process

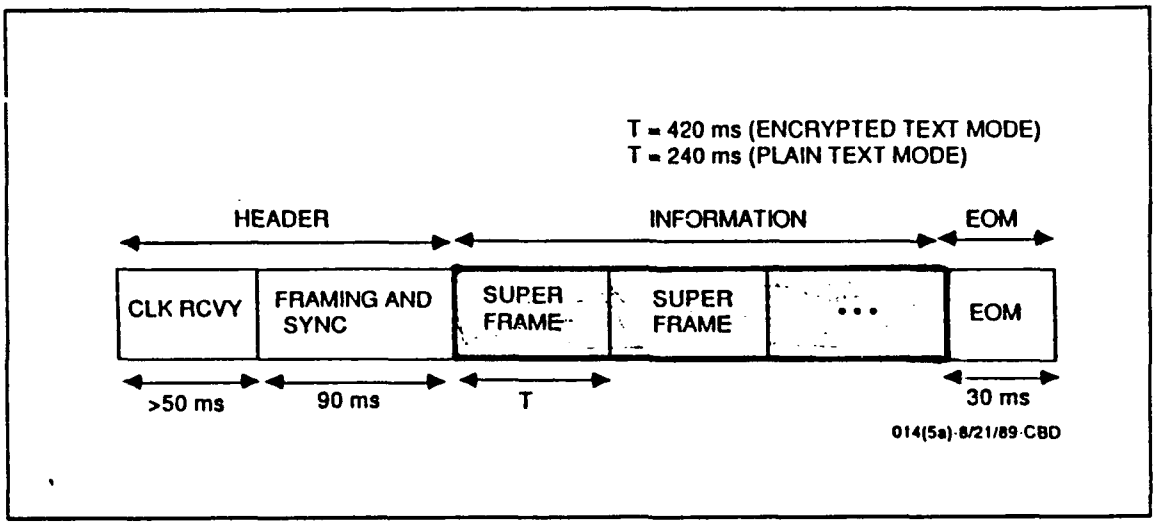

Figure 2. Transmission Format (Source: GTE Government Systems Corp., LMR program review, Waltham, MA)

explained below. Three levels are depicted in Figure 3 on page 10. The top level depicts 8000 bits or 8000/3360 = 2.38 superframes. The next level shows the superframe broken down into the fourteen 30 msec frames. Finally in the lowest level, one of these 240 bit frames shows the arrangement of the 16 interleaved bits within one frame. Of the 14 frames, frames 4 through 12 (only) contain the MI bits and MI EDAC (or "parity") bits.

B. PROPOSED INTERLEAVING

The process of *interleaving* involves dispersing critical bits over the superframe, in regular fashion, so that there is a smaller chance of these bits being corrupted by noise bursts. Interleaving ensures, for example, that the 72 MI bits and the 72 MI parity bits are spread in a pre-determined arrangement throughout the superframe. In this way a long noise burst will not corrupt these critical portions of the message. If the bits were grouped together, even a 10 ms burst (80 bits) could destroy the usefulness of the entire MI, and prevent successful cryptographic synchronization. Instead, by using an interleaving technique, only

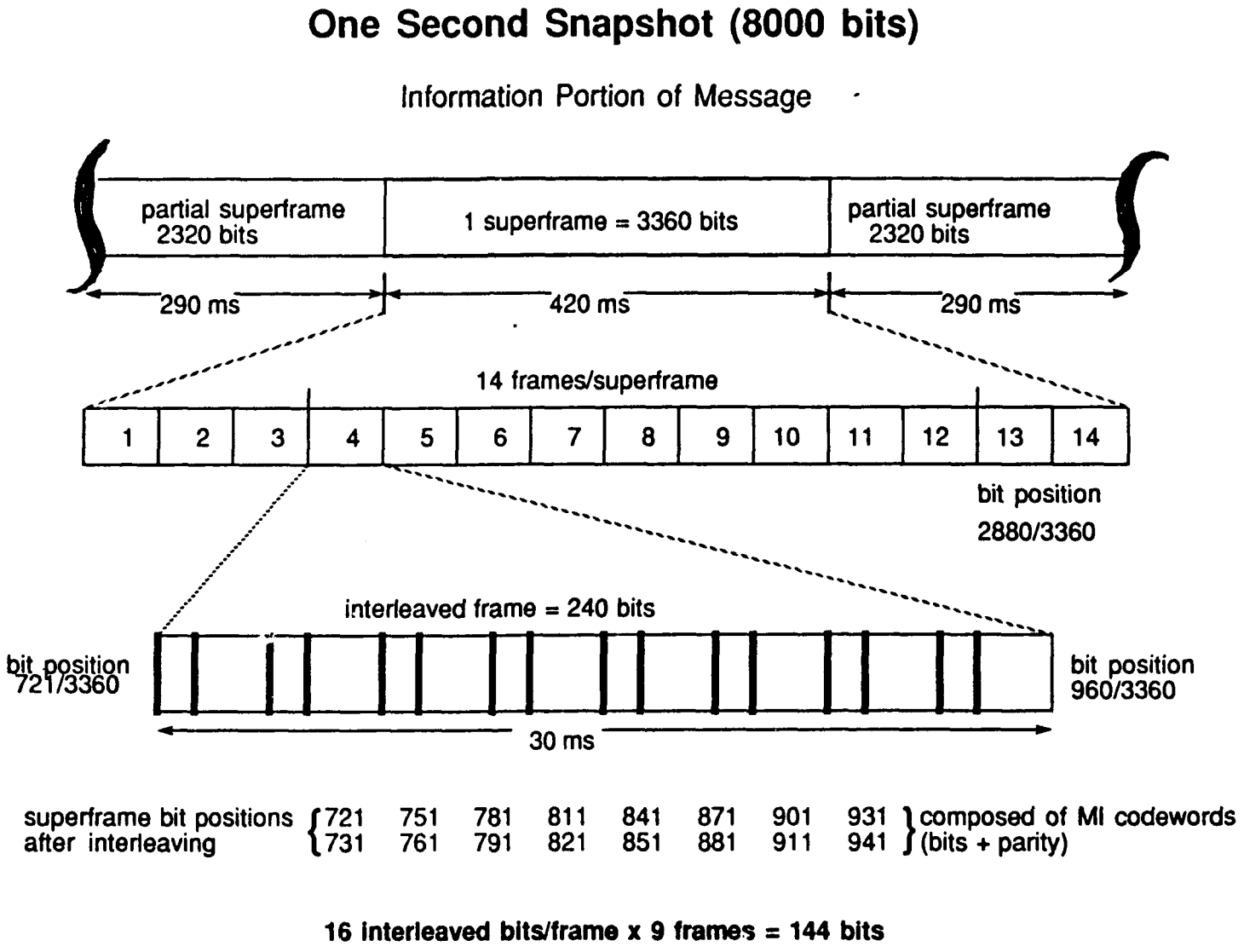

Figure 3. Transmission Structure Breakdown

a few of the critical MI bits may be corrupted; these should be detected and corrected by the interleaved MI parity bits. [4]

An evaluation was performed by GTE on two proposed interleaving schemes (I and II) for the FS 1024 superframe format [Ref. 12]. The testing was performed using mobile vehicles communicating in an urban environment. Scheme II outperformed Scheme I for vehicle speeds approximately three times slower in the five LMR frequency bands (132-172MHz, 406-420MHz, 450-512MHz, 806-512MHz and 851-866MHz).[5] This is because the EDAC codewords (MI bits + parity bits) are more evenly interspersed over each frame in the Scheme II interleaver. The subsequent description and analysis address interleaver scheme II only, since FS 1024 will likely incorporated that scheme.

Figure 3 on page 10 also shows the interleaving scheme used by the EDAC computer simulation described in Chapter IV. Frames 1 through 3 are reserved for framing and mode control bits; Frames 13 and 14 contain system control bits. Every frame contains the voice - CELP processed information bits and its parity bits. The interleaving of MI bits and MI parity bits begins at the beginning of frame #4 or bit 721 and alternates skipping first 10 bits then 20 bits then 10 bits, etc. all the way through the frame #12 ending at bit 2680. Appendix C includes three codeword interleaving tables, one each for the Golay (24,12) code, the QRC (48,24) code and for the Hamming (8,4) code. The MI bits plus their parity bits (or "codewords") are broken up differently for the Golay, QRC, and Hamming codes to achieve maximum spread over frames 9 thru 12, the interleaving frames. For QRC the codewords are broken up into 4 bit chunks, for Golay the codewords are broken up into 2 bit chunks and for Hamming 1 bit chunks.

Figure 4 on page 13 illustrates frame composition for the QRC (48,24). For the QRC there are 3 codewords required (3 x 48 bits = 144 bits). Each codeword

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4 More critical, however, is the interleaving of the MI parity bits. For if non-interleaved parity bits were corrupted by a noise burst, then MI bits also corrupted by another random noise burst would have no chance of being detected and corrected by the chosen EDAC scheme. At the very least, then, MI parity must be interleaved. Because of the random nature of noise however, both MI bits and their parity bits are both, optimally, interleaved.

5 For both schemes the lowest frequency band had the worst performance.

block pictured is a piece of one of the 3 codewords taken 4 bits at a time. All bits other than these 144 out of 3360 bits/superframe are treated as "don't care" within the analysis program. The EDAC protection of the information bits (CELP processed voice) was analyzed by NSA/R556 using Golay (hard and soft decision) code [Ref. 2].

In Chapter III, block codes and the codewords used for each code will be discussed in more detail. Most importantly, each code will be examined in terms of its ability to detect and correct errors.

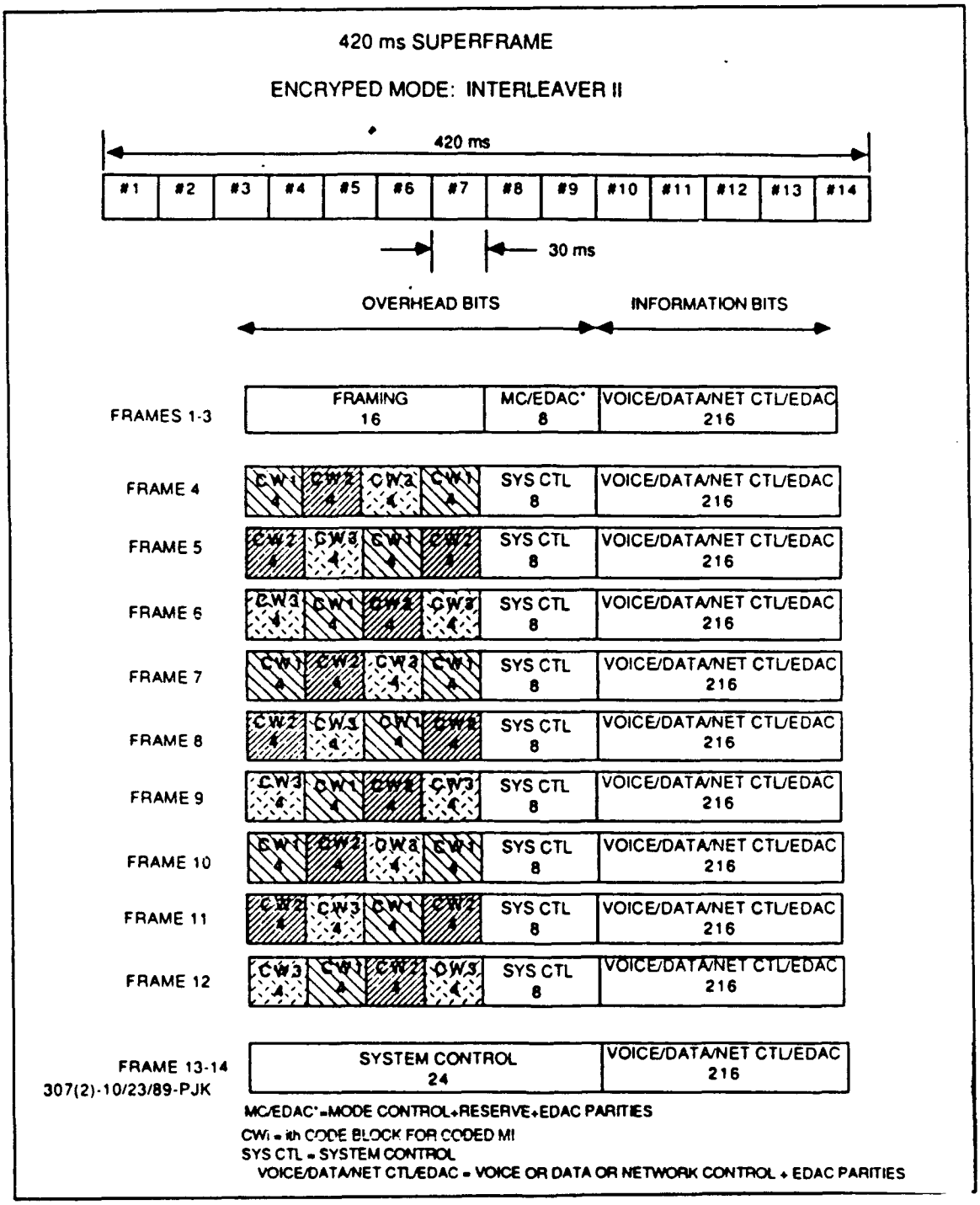

Figure 4. Superframe Composition (Source: GTE Government Systems Corp., LMR program review, Waltham, MA)

III. EDAC CODES EXAMINED

A. INTRODUCTION

All of the codes examined in this thesis -- Golay(24,12), QRC(48,24), and Hamming(8,4) are either in the class of (n,k) block repetition codes or (n,k) cyclic block codes. For n total bits/block and k information bits/block, the number of parity bits equals (n-k), and code rate R = k/n. All of the codes have a code rate R = 1/2, which lends itself to easier bit manipulation.

For block codes, a generating polynomial, $g(x)$, is used to determine the parity checks performed. The number of parity bits determine the the number of checks performed. This parity check group is formed into a check matrix or **H matrix** for ease of manipulation.

The n-bit blocks (or "codewords"), formed by the product of the encoder (the parity bits) and information bits, becomes the transmit vector, $V(x)$. The received vector, before decoding, is designated $R(x)$.

Prior to decoding, a *syndrome* is used as a binary number block by the code algorithm to mark errors and the position of the errors for correction. If the syndrome equals zero, then there are no errors. The decoding and correction of the bits are algorithm dependent. Several different decoding schemes may be possible for each code.[6]

The number of possible errors corrected for a code is determined not only by the codeword size (n) and the information stream length (k), but by the minimun *Hamming distance*, d_{min}. This distance is the minimum number of bits that differ among all pairs of codewords in the code set [Ref. 16: p. 23]. The code can correct $1/2(d_{min})$ number of errors if d_{min} is even and $1/2(d_{min} - 1)$ errors if d_{min} is odd.

B. GOLAY CODES

The *perfect* cyclic Golay (23,12) code is a triple-error correcting code, and can be implemented in software. Typically, one extra bit is added to parity yielding

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6 For derivations and more study on linear block codes refer to [Refs. 13, 14, and 15].

the Golay (24,12) code. This is done to maintain code rate = 1/2 and ease of algorithmic manipulation. The generating polynomial used is:

$$g(x) = x^{11} + x^9 + x^7 + x^6 + x^5 + x + 1$$

The Golay (24,12) code can be improved by utilizing analog information asssociated with the channel bits. In this way the bit error rate in white Gaussian noise can be improved about 2 dB. [Ref. 17] This "soft" decision-making uses the value of the previous baud to calculate confidence intervals. These confidence values are *real* values rather than actual baud values. This concept is illustrated by the constellation, Figure 5 on page 16 [Ref. 2].

The X and Y axes of Figure 5 on page 16 represent the least significant bit (lsb) and the most significant bit (msb) decision boundaries of the two baud being compared. The dot represents the unquantized phase difference between present baud and previous baud and the circle represents the magnitude at the present baud relative to the low-pass filter receive baud magnitude. The confidence for each sb is then the phase difference from the dot to its corresponding nearest boundary. Fades are flagged by scaling the amplitudes of the confidence values.

Sixteen iterations (2^4 bit patterns) are performed to search for and invert the bits designated by the Golay decoder as the lowest four confidence bits in the codeword. The errors are counted for each iteration and the bit pattern with the lowest cumulative confidence is selected as valid.[7]

For both Golay decisions, there are 6 codewords (24 bits codeword x 6 codewords superframe = 144 bits) generated for every superframe for the simulation.

C. HAMMING CODES

The Hamming (7,4) codes is a single error correcting code where all combinations of two errors are detected; only one error may be both detected and corrected. This code was the first error detection and correction code discovered, in

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[7] Bauds 10, 00, 01, and 11 correspond to phase changes 45, 135, -135, and -45 degrees, respectively.

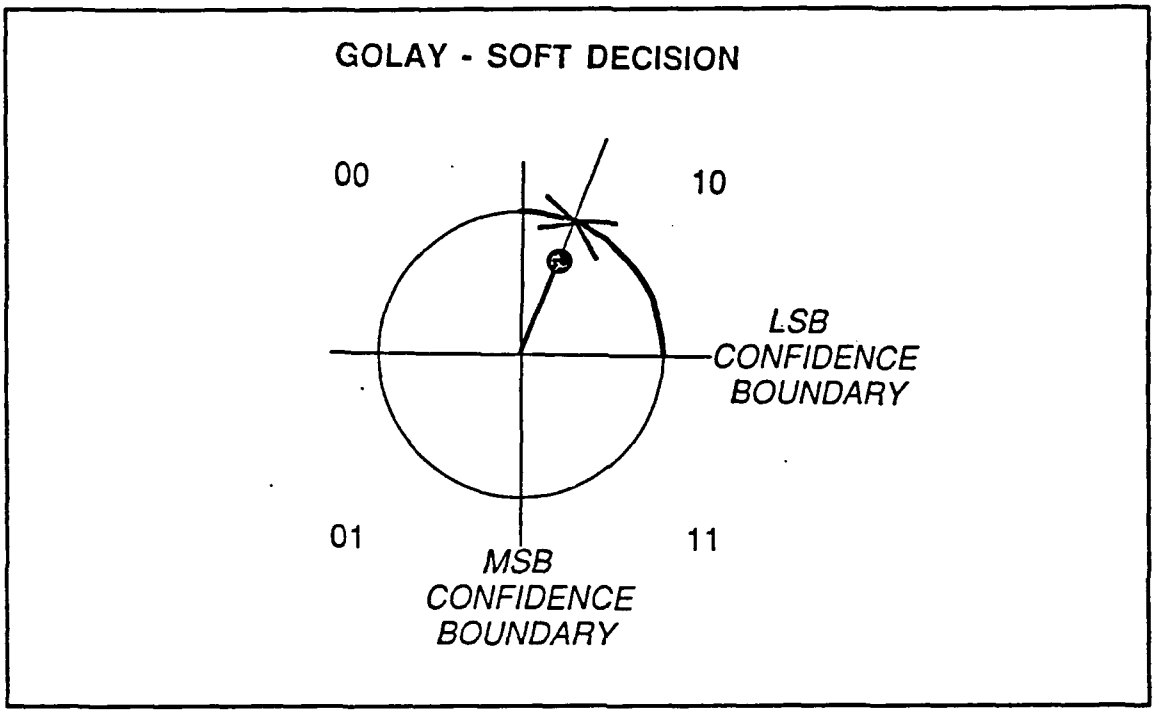

Figure 5. Confidence Constellation [Ref. 2]

1949 by R.W. Hamming [Ref. 18 : p. 13-29]. The modified (8,4) Hamming code is used for this analysis, where, 1 parity bit is added to maintain code rate $R = 1/2$.

For the simulation, there are 18 Hamming codewords (8 bits/codeword x 18 codewords = 144 bits/superframe) generated for every superframe.

D. QUADRATIC RESIDUE CODE (QRC)

Quadratic residues are used to specify the roots of the code generator polynomial [Ref. 19: pp. 92,93]. They are defined by the numbers,

$$1^2, 2^2, 3^2, \ldots, \left(\frac{p-1}{2}\right)^2$$

which are mod p reduced, where p is an odd prime number. Nonresidues are the numbers in the quadratic group that are not included by the residues. For ex-

ample, if $p = 19$, this would include all the mod 19 residues for $1^2, 2^2, 3^2, \ldots, 9^2$. The following table, Table 2 on page 17, shows these values.

Table 2. QUADRATIC RESIDUES FOR P = 19

	residues	non-resid
$1^2 = 1$	1	2
$2^2 = 4$	4	3
$3^2 = 9$	9	6
$4^2 = 16$	16	8
$5^2 = 25$	6	10
$6^2 = 36$	17	12
$7^2 = 49$	11	13
$8^2 = 64$	7	14
$9^2 = 81$	5	15
		18

The QRC investigated by GTE is the (48,24) code, with $p = 47$. This code is capable of detecting and correcting 100% of 5 (or fewer) bit errors and 62% of 6-bit errors. The probability of correcting 6-bit errors is calculated with combinatorial logic as follows.

$$(47,24) + 1 \text{ parity bit} = (48,24)$$

The number of 5 or less correctable errors is:

$$C(47,5) + C(47,4) + C(47,3) + C(47,2) + C(47,1) = 1,729,647$$

Also, the codeword with one error must be accounted for, C(47,0) = 1. Since there are 2^{23} possible parity vector values (8,388,608),

$$8,388,608 - 1,729,647 - 1 = 6,658,900$$

is the number of possible parity comibinations remaining to map into 6 or more error combinations. Next, the number of 6-bit errors possible within the 48 bit codeword is:

$$C(47,6) = 10,737,573.$$

Therefore,

$$6,658,960 \div 10,737,573 = .6202$$

This implies that the QRC will correct the sixth error in a 48 bit codeword 62.02% of the time.

There are 3 QRC codewords (48 bits/codeword x 3 codewords = 144 bits/superframe) generated for every superframe in the simulation.

The implementation of these EDAC schemes into a transmission simulation model will be discussed in Chapter IV. Also, the testing design approach and channel simulation models are introduced the next chapter.

IV. TESTS AND SIMULATION

A. DESCRIPTION OF THE PROGRAMS PROVIDED

1. Introduction

The program used in this analysis was provided by DIRNSA/R556, and was previously used by DIRNSA to evaluate the use of Golay (hard and soft decision) coding for the protection of the CELP information bits. A separate subroutine of the Hamming code was also provided, for integration into the main program. Program subroutines neatly divided most of the program chores (i.e. bit generation, encoding, modulation, decoding, bit error count, etc.).

2. Modifications

The program code was loaded and run on a VAX 11/785 mainframe in the ECE Department at the Naval Postgraduate School after conversion from Sun III FORTRAN to Berkley FORTRAN 77. The program was further modified to incorporate the Hamming code simulation and a bit error counter for the QRC. The encode decode functions of the QRC are not included in the simulation - only a counter based on the code's probability of error detection and correction within a codeword.[8]

B. SIMULATION DESCRIPTION

Figure 6 outlines the simulation process in block fashion. The process begins as a pseudorandom (PN) bit stream, representing the MI bits, is produced for each superframe. Next, the 72 MI bits are encoded by the chosen EDAC, with "no code" representing the default control. The encoder generates the 72 parity bits to formulate a completed codeword of 144 bits.

The 144 bits are then hashed. This hashing process is in reality a pre-interleaving step that enhances the spread of the codeword bits throughout the

---

[8] At this writing GTE is looking at simulating the QRC. However, the algorithmic implementation is much more complicated than even the Golay codes. Therefore, actual QRC encoding and decoding is not attempted in this analysis.

superframe.[9] For each codeword the first bit is stacked, next the second, the third and so on. These realigned bits are then interleaved in Scheme II fashion, as described in Chapter II. To fill the rest of the 3360 bit superframe, an arbitrary PN bit stream is produced. The codeword bits are interleaved among these fill bits.

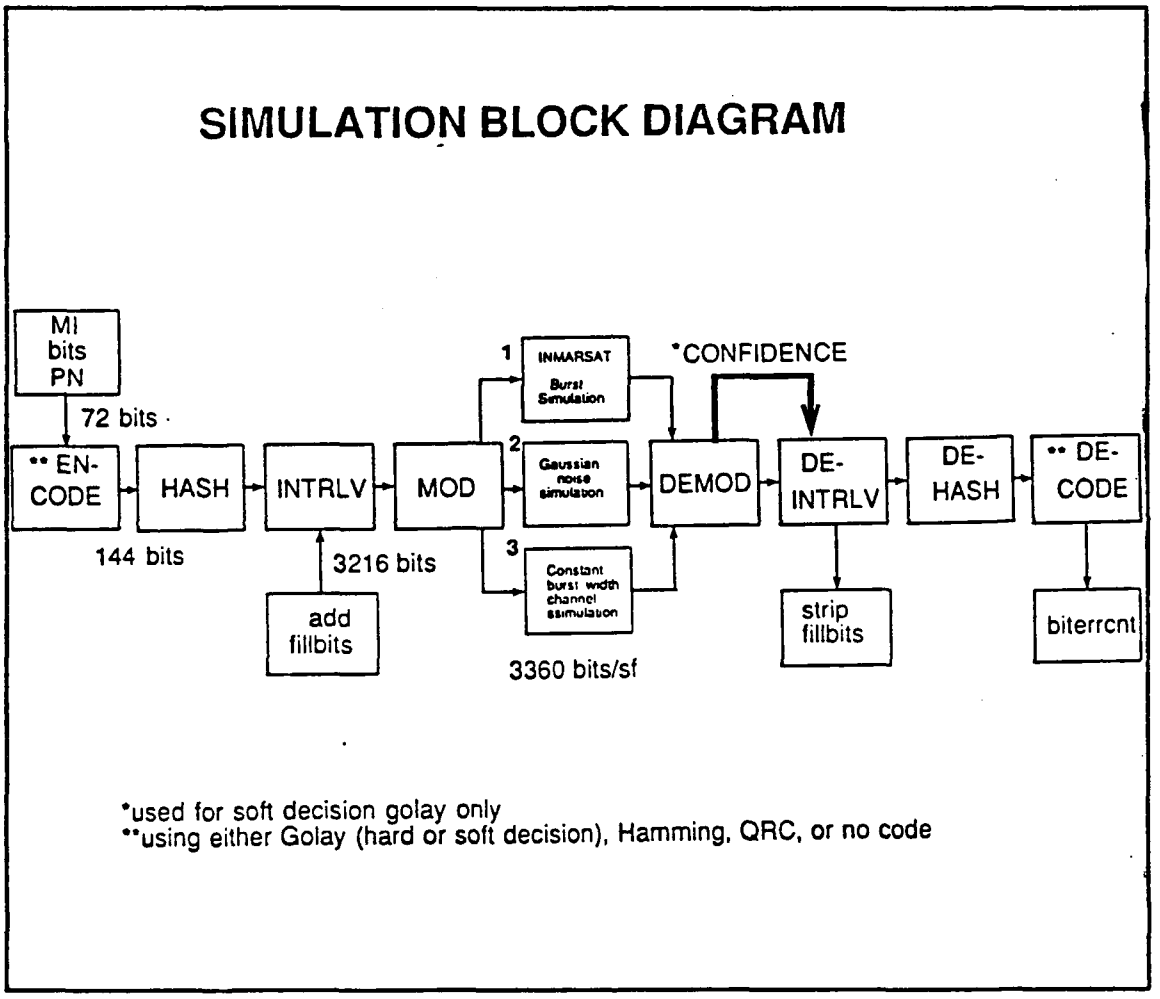

Figure 6. Simulation Block Diagram

Before modulation and transmission, the bits are changed to baud using a dibit representation as shown in Table 3 on page 21. The entire superframe is modulated and transmitted, then sent over one of three user-chosen simulation

9 This process is not reflected in the codeword interleaving table in Appendix C.

channels. The transmitted bits, now with simulated errors, are received and demodulated, deinterleaved, stripped of the 3216 non-applicable bits, de-hashed, decoded and checked for errors.

Table 3. BIT/BAUD EQUIVALENT

dibit	baud
0 0	0
0 1	1
1 0	2
1 1	3

Figure 7 illustrates the simulation design approach. Each section of the matrix represents one simulation run, for a total of 80 runs (5 codes x (1 INMARSAT CH + 8 AWGN CH + 7 constant burst CH)). A simulation run consists of 200 consecutive superframes. In all cases, the first superframe was expended for synchronization purposes. Thus, there are 199 x 420 ms or 83.58 seconds of established continuous information flow, which is likely much greater than an average message transmission. During the 83.58 second period, continuity of the digital signal is maintained unless bit synchronization is lost due to fade or noise.

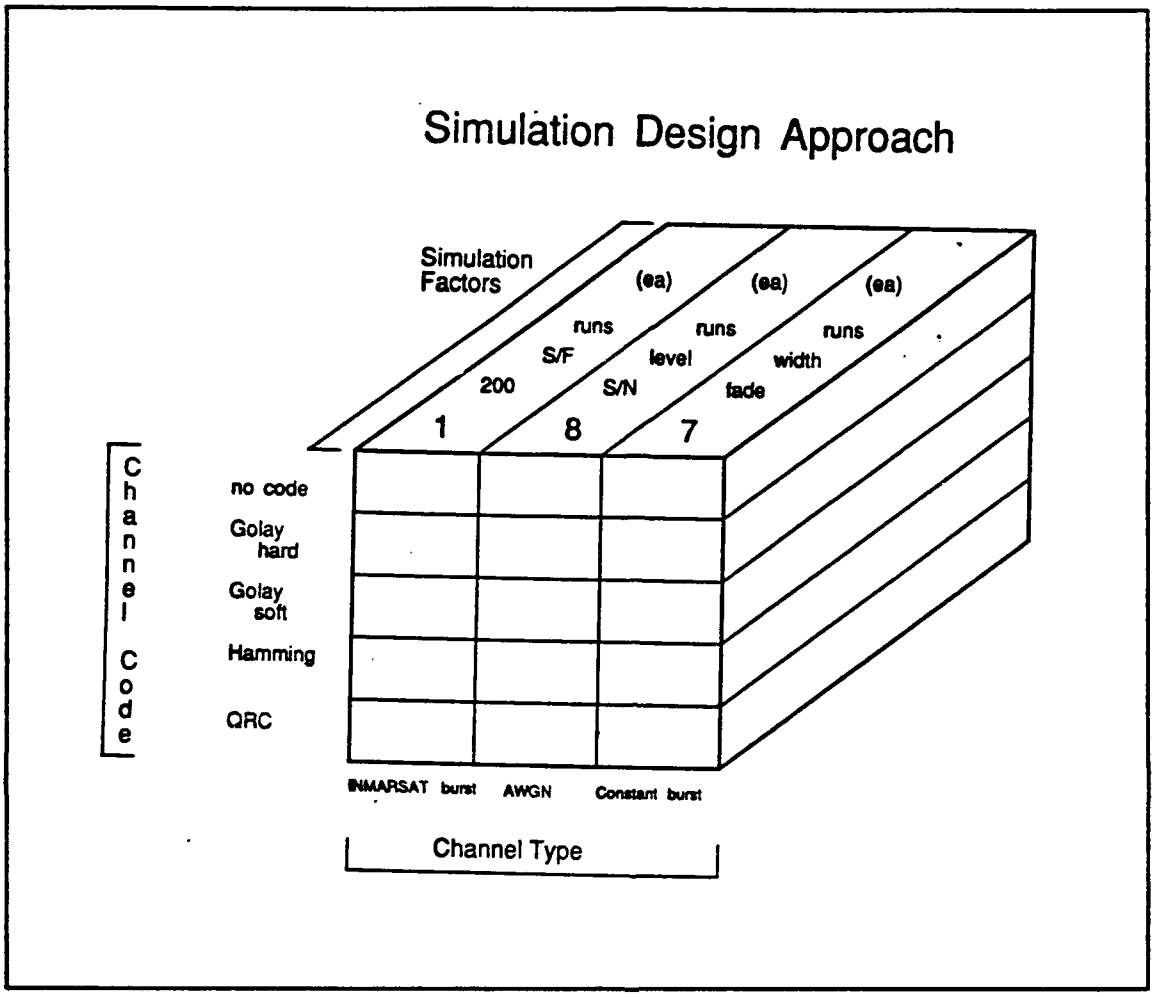

Figure 7. Simulation Design Approach

All simulation runs record the number of errors (within the 144 EDAC bits/superframe - location of an error is unknown) out of the total number of EDAC bits processed. Also, the number of successful and failed (S/F) superframes are recorded. Even one uncorrected error results in a superframe failure.

C. CHANNEL SIMULATIONS

The "mode" and "vary" variables provided for each channel are simulation selectable variables which determine the channel simulation mode.

For the simulation model, during *fading* or burst mode sequence the signal was subjected to -24 dB S/N and the signal strength divided by 200. This was

injected to ensure a 50% Bit Error Rate (BER) during burst error as required by the INMARSAT model. During non-burst error intervals, the S/N could be at any level. This parameter is user specified. For the two burst channel simulations, the S/N was set equal to 99.0 dB to ensure a clean signal. Therefore, *all of the errors* are a result of the signal fade. In the Gaussian channel the S/N parameter was varied from 0 to 7 dB. For the Gaussian channel, simulation errors were a result of poor S/N levels only.

1. INMARSAT Burst (mode = 1,vary = 0)

For the random burst noise (signal fade) channel simulation, the "simplified Land Mobile Radio channel model for IMARSAT Codes Evaluation Proposal (ICEP)" was used [Ref. 20: pp. 9,10]. The model is described as follows:

> "The model is derived from realistic empirical propagation measurements such that performance of voice codecs can be tested in the laboratory with replicable situations. 90% is chosen as the link availability figure in the simplified model. The model is basically an ON-OFF model in which fading is in a binary state. The ON-state should correspond to no transmission whereas the OFF-state corresponds to 50% BER."

The discrete probability density function (PDF) for the permissible noise burst widths are shown in Table 4 on page 24. The distribution of the burst widths for the INMARSAT channel is base on a random process. Therefore, the number of bursts for each burst width varied. For all but 200 msec burst widths, the actual number of bursts for each burst width were not significantly different from that predicted by the PDF.

Table 4. SIMPLIFIED FADE DURATION PDF

Fade (ms)	Prob
10ms	0.8
20ms	0.1
40ms	0.05
100ms	0.04
200ms	0.01

For the burst-noise channel simulation, one 200 superframe run was performed for each of the four codes and one run with no coding. An example of 3-second Golay-encoded signals, transmitted over an INMARSAT burst-noise channel, is shown in Figure 8 on page 25.

2. AWGN Channel (mode = 0,vary = 0)

For the additive white Gaussian noise (AWGN) channel simulation, signal-to-noise ratio (S/N) was varied from 0 to 7.0 decibels (dB) in 1.0 dB increments. Thus forty simulation runs (5 code modes x 8 S/N levels) were performed.

3. Constant Burst Width (mode = 1,vary = 1)

For the constant burst width channel simulation, a constant fade depth (or burst width) was inserted at random time intervals. Seven discrete fade widths -- 5, 10, 20, 40, 100, 200, and 400 milliseconds -- were run for each code. Thus, thirty-five simulation runs (5 codes x 7 burst widths) were performed, each having 200 superframes. The 5 and the 400 msec burst widths, not included in the INMARSAT model, were added to observe the limits of the model and the performance of the codes.

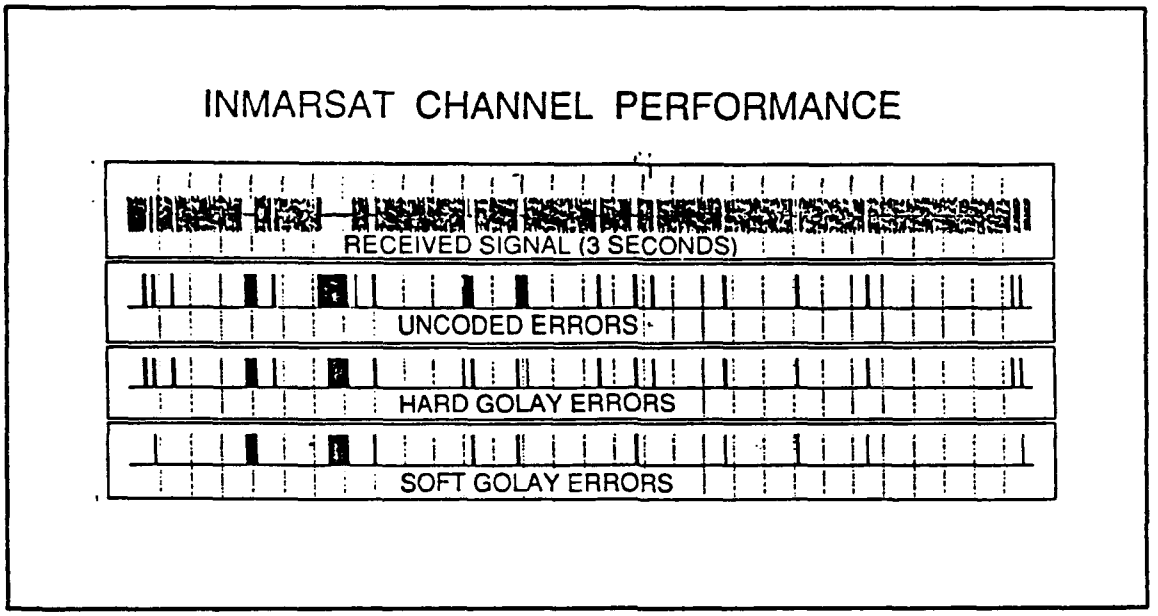

Figure 8. INMARSAT Channel Performance [Ref. 2]

Figure 9 shows constant amplitude signals subjected to varying fade widths. One second translates to 2.38 superframes.

Using the same outline as Chapter IV, the test *results* are presented in Chapter V by channel simulation type. The BER results and S/F results for each simulated code over each of the three channels is displayed and compared.

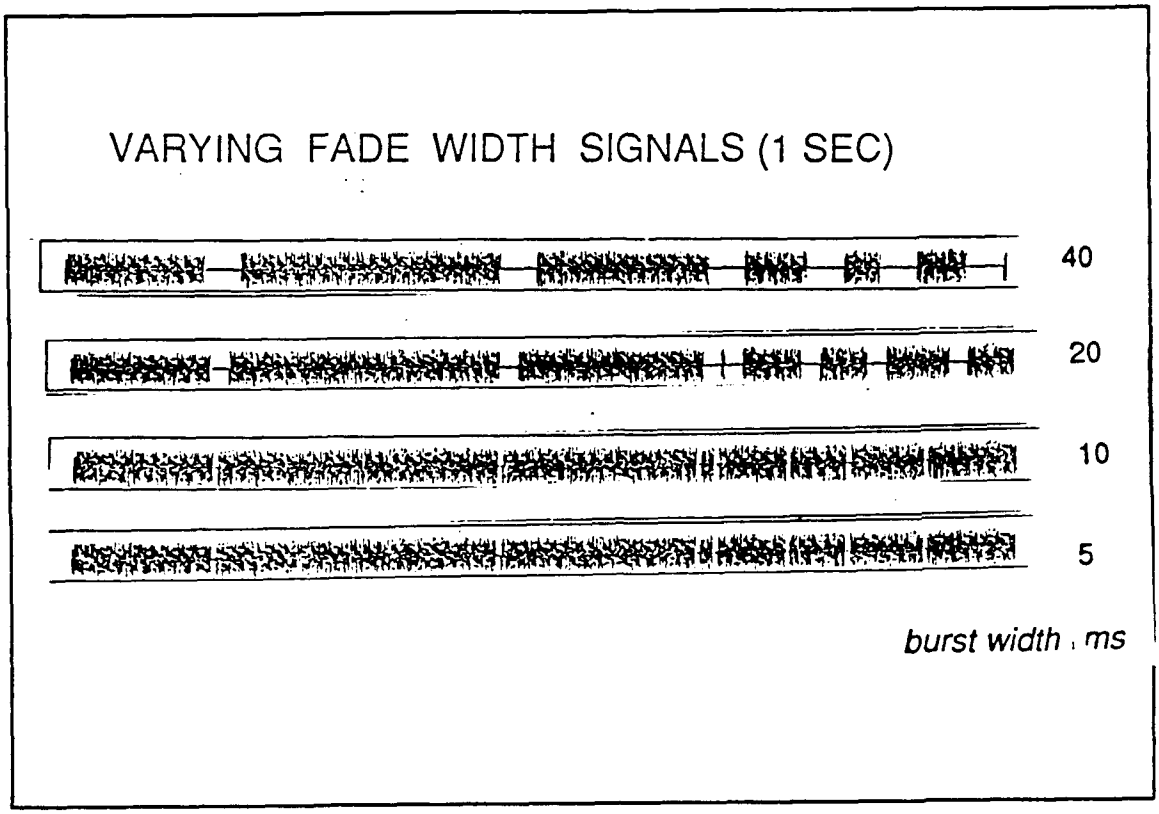

Figure 9. Varying Fade Width Signals [Ref. 2]

V. COMPARISON AND ANALYSIS OF TESTS

For each of the three simulated noise channels, the codes are rated in terms of BER performance and in terms of number or percentage of successful (or "error-free") superframe transmissions. BER results are expressed as the BER exponent.[10] This number is calculated by taking the $\log_{10}$ of the number of errors counted divided by the number of bits transmitted.

The code abbreviations used in data tables are:

- **g(s)** - soft decision Golay (24,12)
- **g(h)** - hard decision Golay (24,12)
- **none** - no channel coding
- **ham** - Hamming (8,4)
- **QRC** - quadratic residue code (48,24)

A. INMARSAT BURST CHANNEL

1. BER Results

Table 5 on page 27, reflects BER results as the log of the quotient (number of errors counted divided by the number of bits transmitted). All BERs are greater than $10^{-1.2}$ for this simulation, which implies greater than 1 error out of 100 bits. These performance values are intuitively reasonable for LMR operations in an urban environment.

Table 5. A FUNCTION OF INMARSAT BURST NOISE, ALL CODES

	g(s)	g(h)	none	ham	QRC
BER exp	-1.5003	-1.4342	-1.3363	-1.5243	-1.8153

Also, the difference between the hard and soft Golay is only about 0.5%, while the QRC outperforms the soft Golay by more than 1.6%. This may be a reflection of the number of "long" bursts. For the pseudo-random process, the

10 The convention in [Ref. 2] was followed.

g(s) suffered eight 200 msec fades while the QRC was only forced to process 2. If these additional bursts happened to span the critical MI bits in the g(s) codewords, the BER would have increased.[11] Looking at the INMARSAT PDF, Table 4 page 24, the 200 msec bursts only have a 1% probability of occurrance. The difference between the number of 200 msec fades for the g(s) and the QRC runs is therefore, insignificant.

Figure 10 on page 29, derived from table 5, shows the BER performance advantage that the QRC has over the other codes for this simulation. The QRC detected and corrected 1.5% more errors than the g(s).

2. Run Success/Failure Results

Table 6 on page 28 reports the number of successful runs in the simulated INMARSAT channel, for each code.[12] While BER performance favors the QRC in an INMARSAT noise channel, the QRC only ran an additional two successful superframes out of 199. That is less than a 1% performance difference. Nevertheless, the QRC and g(s) are noticeably superior than the other codes and the uncoded channel.

Table 6. INMARSAT BURST - #SUCCESSES/#FAILURES

	g(s)	g(h)	none	ham	QRC
#successes	171	162	81	134	173
#failures	28	37	118	65	25
#total runs	199	199	199	199	198
%successful	86	81	41	67	87

11 This simulation did not allow the control of the number of bursts of each width. Therefore, it was impossible to inject the codes with the same error occurances.

12 If the number of successes and the number of failures do not add up to 199, the runs not accounted for are out-of-synchronization (OOS) superframes. If there are too many errors the transmission falls OOS and retries until a success or a failure is achieved. In any of the channel simulations the OOS runs are not counted toward the total number runs.

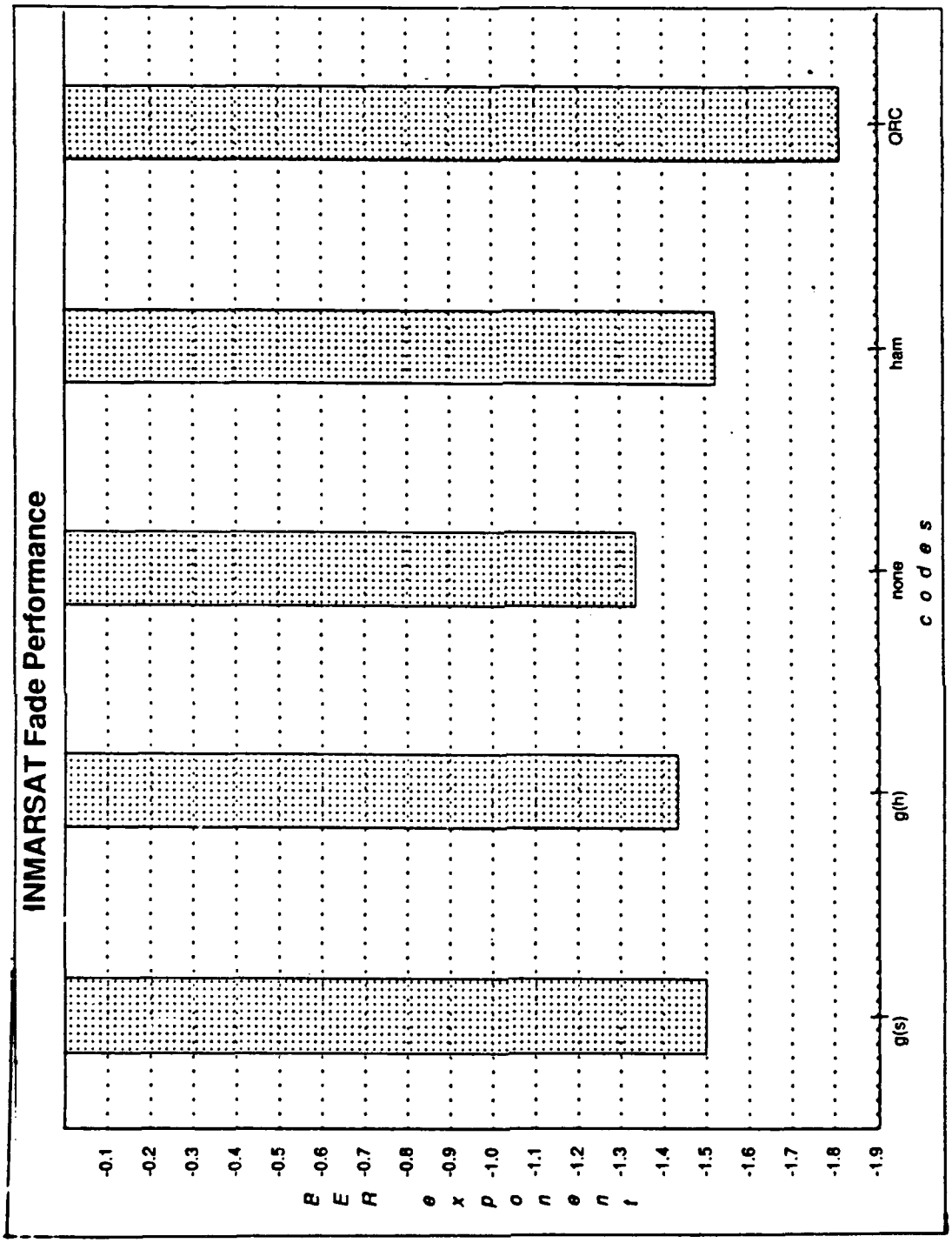

Figure 10. INMARSAT BER Performance

3. Additional Tests

Further testing was performed to check the validity of the INMARSAT simulation results. An additional 1000 superframes were run for both the g(s) and the QRC. Again, the QRC outperformed the g(s) in BER by .62%. The QRC also provided 2% more successful superframe runs than the QRC.

There seems to be a trend, in that the performance difference between the two codes appears to narrow with more superframe runs. This hypothesis could be tested with even more superframe runs. Nevertheless, the BER difference of less than 1% leads to the conclusion that there is no significant difference between the INMARSAT channel performance of the two codes -- g(s) and QRC.

B. GAUSSIAN NOISE CHANNEL

1. BER Results

Table 7 on page 31, tabulates BER exponent for the 40, 200 superframe runs performed in the simulated Gaussian noise channel.[13] Figure 11 on page 32 is derived from Table 7, and shows that g(s) outperforms QRC at S N levels greater than 5 dB. The figure also shows that the g(h) outperforms the QRC at S N levels greater than 6 dB. At S N levels less than or equal to 5 dB, the g(s) offers a slight improvement over that of the QRC and the g(h).[14]

---

13 No errors were counted at 7 dB for g(s) out of codeword bits; the BER exponent of -4.0 was used as a graph limit.

14 For the Hamming code, extra data points were taken; they are reflected in the graph only and not the table.

Table 7. BER AS A FUNCTION OF GAUSSIAN NOISE LEVEL, ALL CODES

	g(s)	g(h)	none	ham	QRC
0	-0.6055	-0.5638	-0.6421	-0.6108	-0.654
1	-0.7447	-0.6615	-0.719	-0.7072	-0.7525
2	-0.9547	-0.8125	-0.8153	-0.829	-0.9014
3	-1.2388	-1.0526	-0.9281	-1.0036	-1.1537
4	-1.6126	-1.3487	-1.0605	-1.2069	-1.556
5	-2.2676	-1.8297	-1.2269	-1.4724	-2.1586
6	-3.2343	-2.8761	-1.4056	-1.7447	-2.6198
7	-4.0	-3.1549	-1.6234	-2.1707	-2.8339

Figure 12 on page 33 is another representation of the same data. Code performance is compared at each S/N level measured. For each code, as the S/N increases the BER decreases. There are no surprising trends for any code. These two factors -- S/N and BER -- are inversely proportional and the comparison chart best illustrates this response. Also, the difference between the codes response at various S/N levels is more easily observed on this comparison chart than on the previous line graph.

2. Run Success/Failure Results

Table 8 on page 34 displays the number and the percent of successful runs with the OOS runs excluded from the total. These calculations were made using the total number of successful runs over the total number of runs performed. The g(s) code outperforms other codes in the gaussian environment, especially at lower S/N, which are more realistic in an LMR environment.

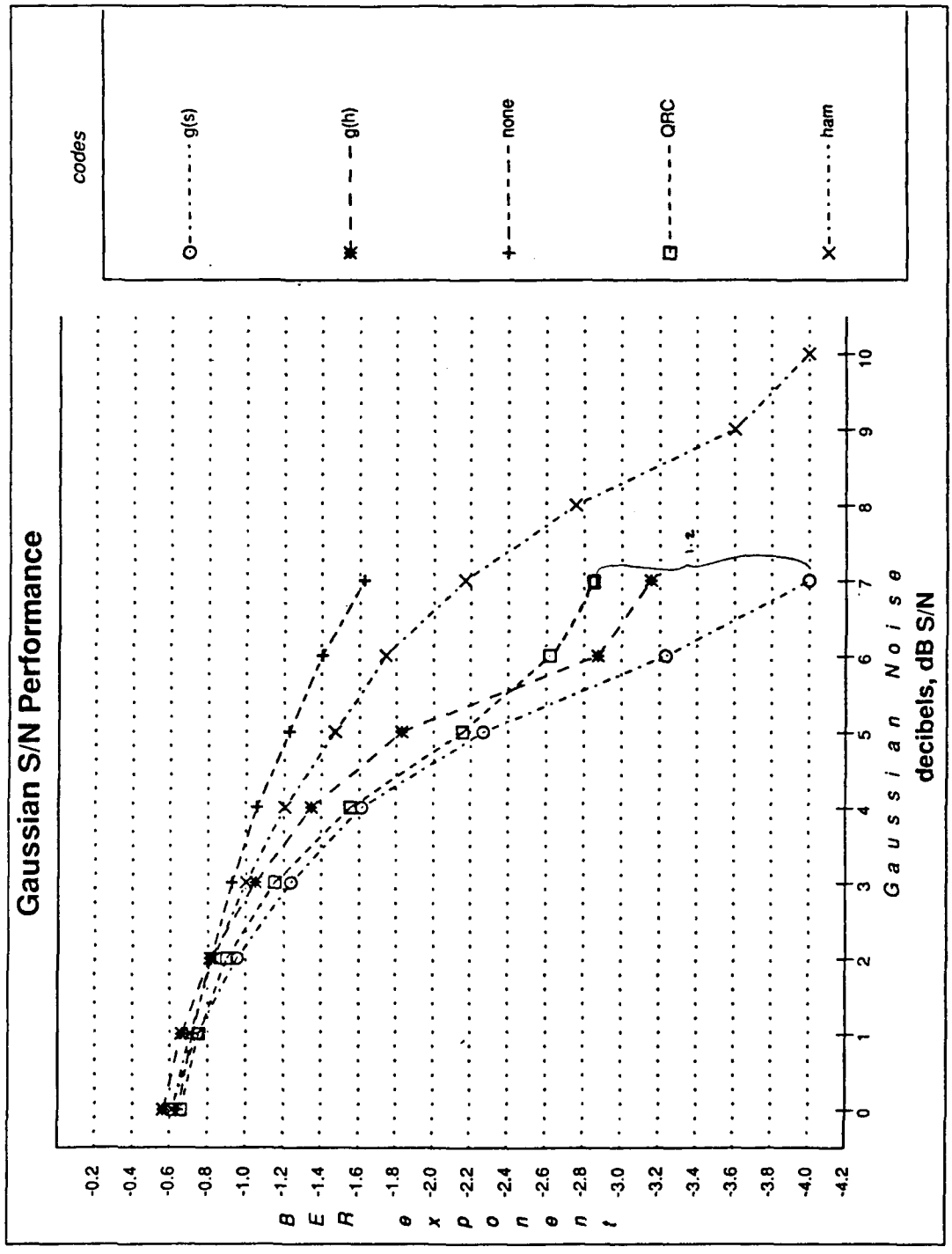

Figure 11. Gaussian BER Performance (line graph)

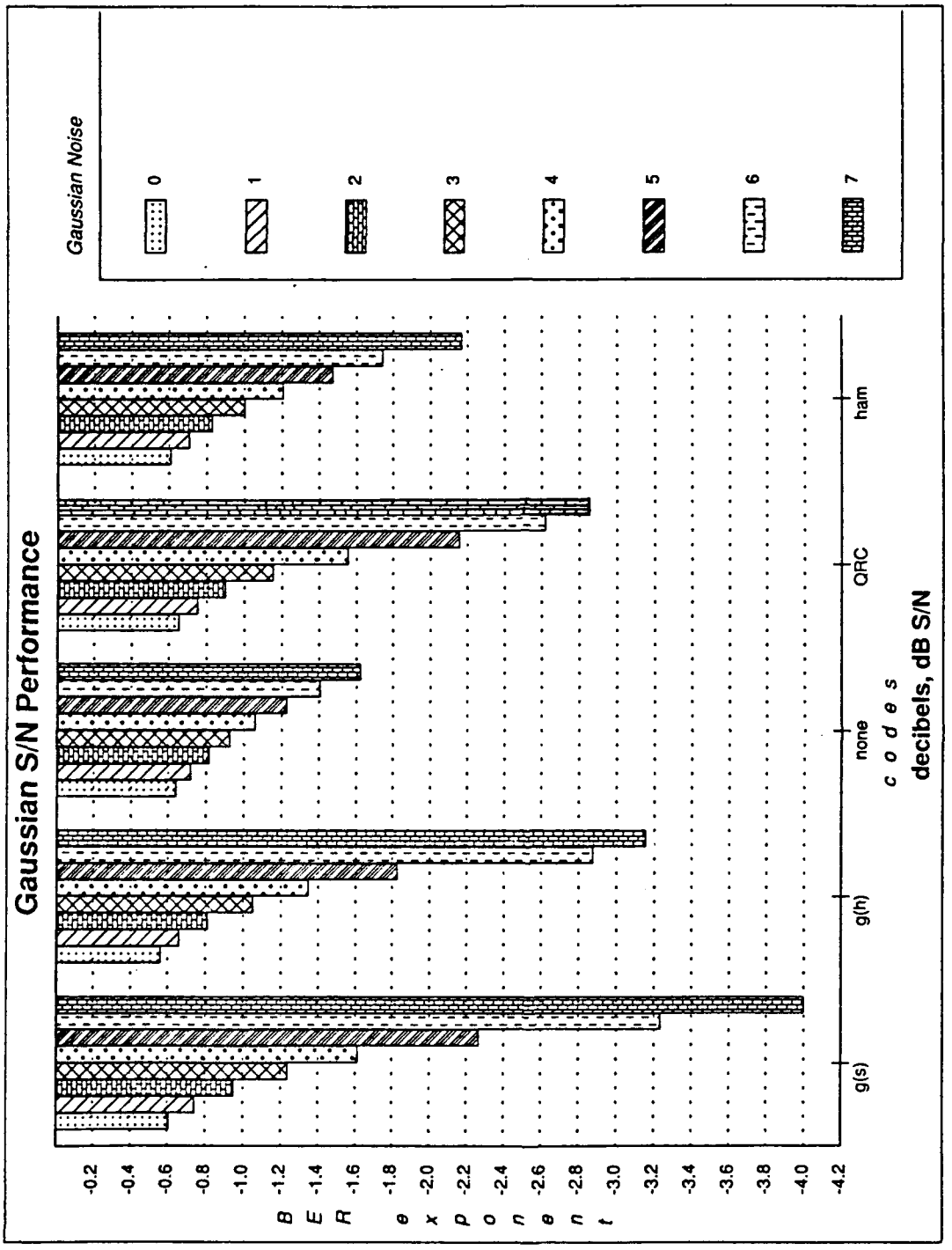

Figure 12. Gaussian BER Performance (bar chart)

Table 8. #SUCCESSES/%SUCCESSFUL RUNS VS. GAUSSIAN NOISE LEVEL, ALL CODES

dB	g(s) # /%	g(h) # /%	none # /%	ham # /%	QRC # /%
0	0/0	0/0	0/0	0/0	0/0
1	2/1.0	0/0	0/0	0/0	0/0
2	19/9.6	3/1.5	0/0	0/0	7/3.6
3	62/31.5	26/13.2	0/0	2/1.3	35/17.6
4	122/61.3	72/36.9	1/0.5	7/3.6	107/53.8
5	175/87.9	140/71.0	2/1.0	41/20.6	177/88.9
6	194/97.5	186/93.5	7/3.5	92/46.2	194/97.5
7	197/99.0	194/97.5	31/15.6	149/74.9	198/99.5
totals	48.6%				45.2%

The line graph, Figure 13 on page 35 compares the percent success of each code in the Gaussain noise channel. For this fiqure of merit, the g(s) code outperforms both the g(h) and QRC, especially at S/N levels between 2-5 dB. The QRC outperforms g(h) at S/N levels between 2-7 dB.

The stacked bar comparison graph, Figure 14 on page 36 compares the overall success of each code, combining all S/N level runs. For total number of runs, g(s) out performs QRC by more than 50 successes.

C. CONSTANT BURST WIDTH CHANNEL

1. BER Results

Table 9 on page 37 represents BER exponents for 35, 200 superframe runs. Figure 15 on page 38 shows the BER performance recorded in table 9, with the area of critical code performance highlighted on the graph.[15] The g(s)

15 From Table 4 page 21). INMARSAT Noise Burst Width: P(10 msec burst) = 0.80; P(10-40 msec burst) = 0.95.

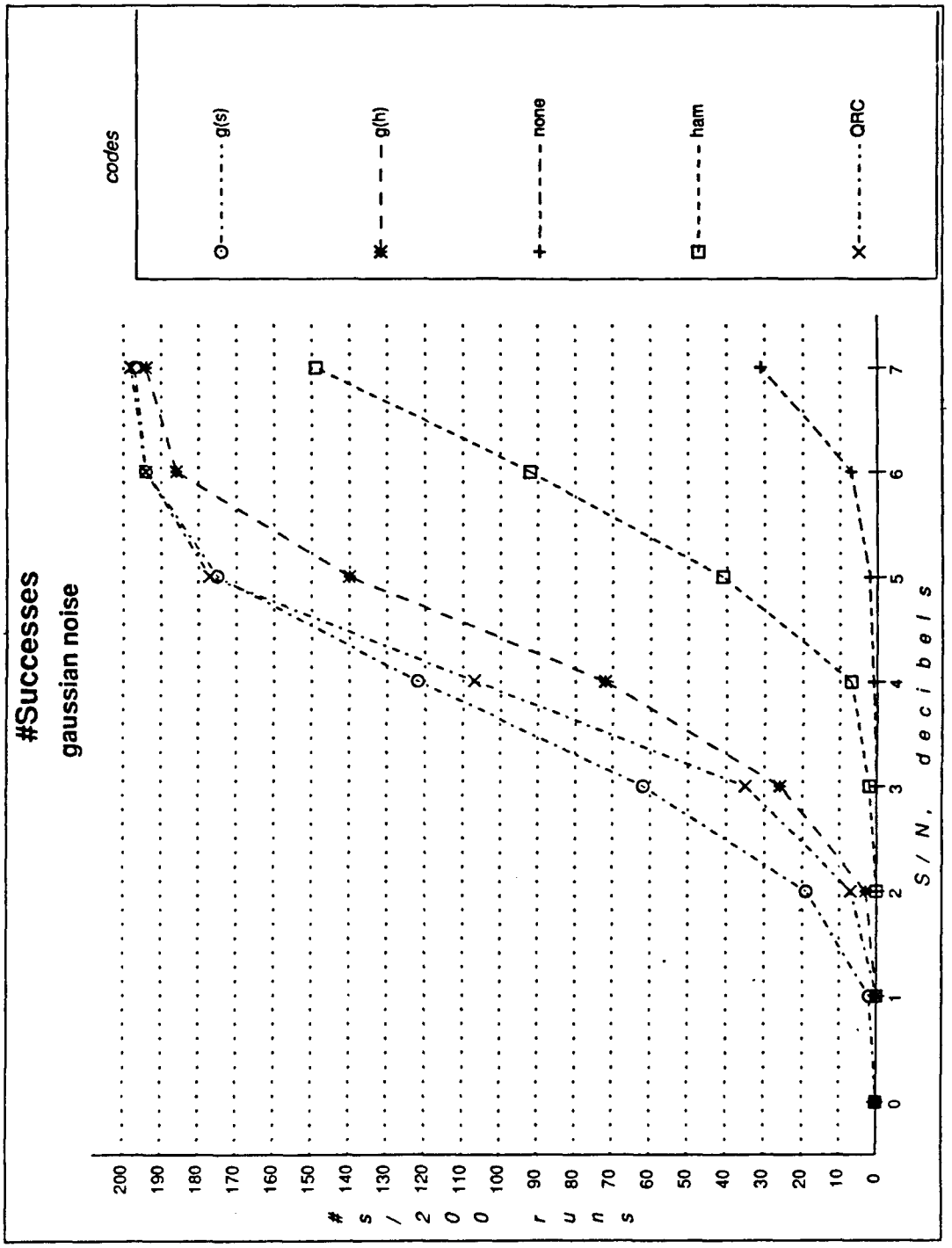

Figure 13. #Successes/%Successful for AWGN channel (line graph)

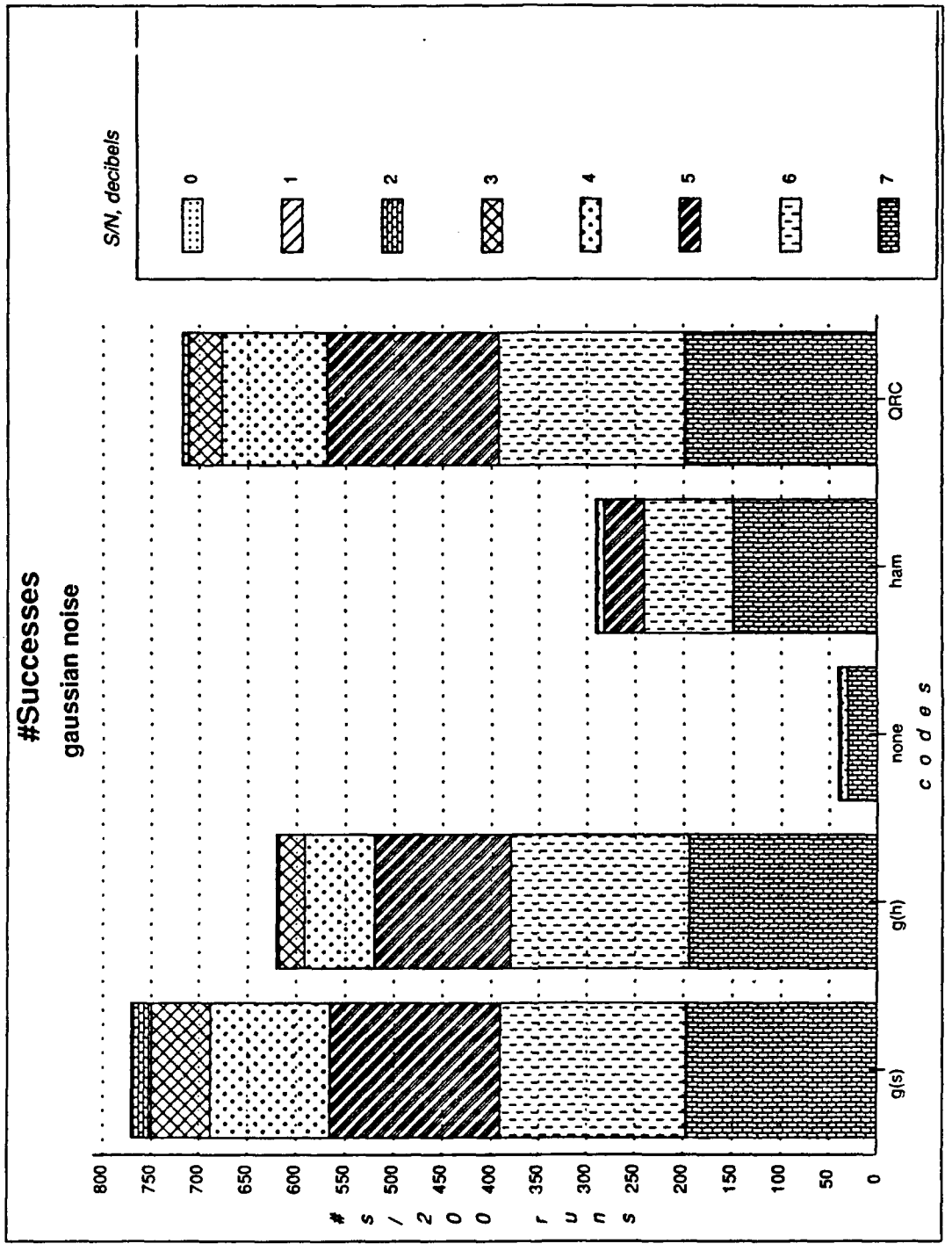

Figure 14. #successes/199 runs for AWGN channel (bar chart)

code outperforms the QRC at burst widths from 10-40 msec; the advantage diminishes at burst widths greater thatn 40 msecs.

Table 9. BER AS A FUNCTION OF CONSTANT BURST WIDTHS, ALL CODES

burst widths	g(s)	g(h)	none	ham	QRC
5	-4.	-2.6021	-1.8297	-2.7375	-2.8447
10	-3.1759	-2.4461	-1.5331	-2.0706	-2.6716
20	-2.0301	-1.9281	-1.2612	-1.5567	-1.9431
40	-1.3516	-1.0516	-1.0419	-1.0956	-1.2048
100	-0.7595	-0.6655	-0.7721	-0.7022	-0.7404
200	-0.585	-0.5229	-0.5544	-0.5089	-0.5786
400	-0.4789	-0.4815	-0.5086	-0.4619	-0.5396

Figure 16 on page 39 also displays the effect that the varying burst widths have on each code. At the 20 msec burst width all three of the codes -- g(s), QRC, and g(h) -- begin to display a similar performance. For a 100 msec burst width condition, *all* codes perform equally poorly. Code response trends -- a consistant increase in the BER exponent as the burst width increases -- are as expected.

2. Run Success/Failure Results

Table 10 on page 40 displays the number and percent successful runs as function of constant burst widths, for all codes tested. At narrower levels of burst width, the g(s) code outperforms the other coded or uncoded channels. The advantage becomes less significant as the width of noise burst exceeds 20 msecs. Again, the g(s) has the overall advantage of 4.9% more successful runs.

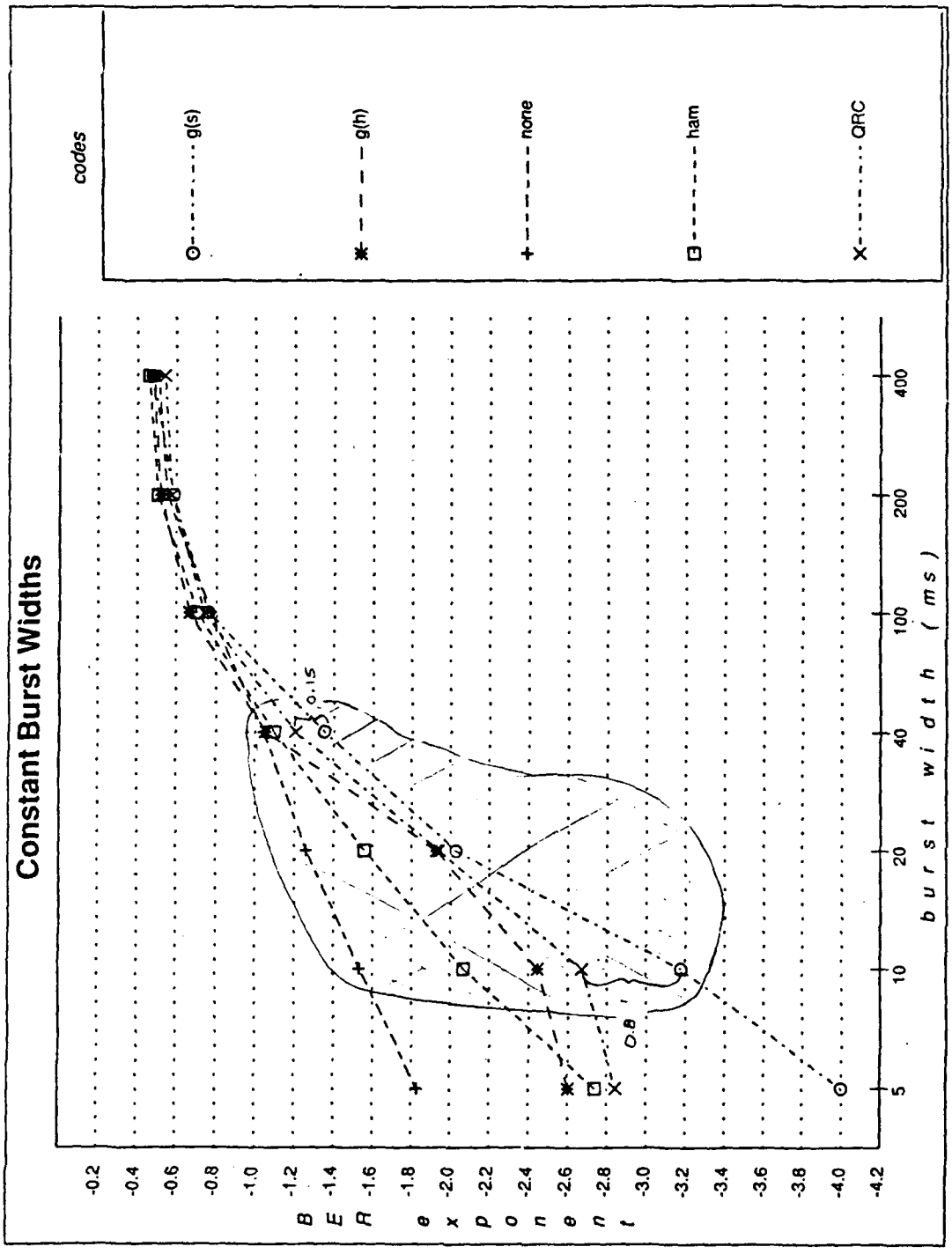

Figure 15. Constant Burst Width Performance (line graph)

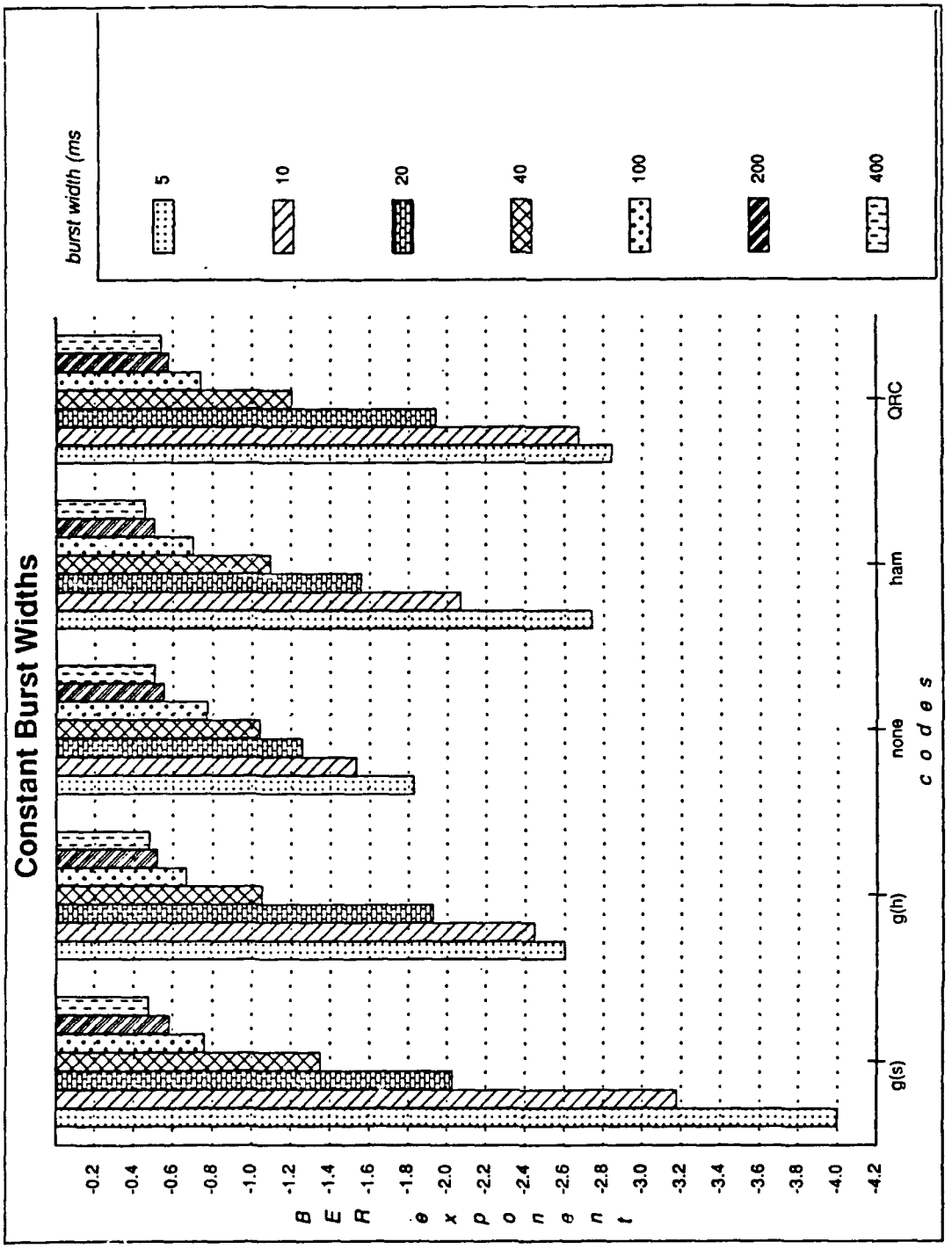

Figure 16. Constant Burst Width Performance (bar chart)

Table 10. #SUCCESSES/%SUCCESSFUL RUNS VS CONSTANT BURST WIDTHS, ALL CODES

burst widths	g(s) #/%	g(h) #/%	none #/%	ham #/%	QRC #/%
5	197/99.5	196/99.5	98/49.2	187/94.0	198/100
10	197/99.0	188/94.5	93/46.7	152/76.4	195/98.0
20	178/89.4	158/79.4	85/42.7	118/59.3	166/83.4
40	139/69.8	97/48.7	74/37.6	77/38.7	107/53.8
100	66/33.2	48/24.1	62/31.5	48/24.1	41/20.6
200	39/19.6	19/12.5	39/20.0	26/13.1	26/13.1
400	1/5.9	0/0	8/30.0	28/14.1	19/11.0
totals	59.7%				54.8%

The line graph, Figure 17 on page 41, compares the relative number of successes for each code. A more robust code with greater interleaver depth may be needed to satisfy performance objectives at these burst widths.[16] The g(s) code performs best, but it's percent success degrades as burst widths exceed 40 msecs. It is interesting to note that the uncoded channel surpasses all codes in performance except the g(s) for burst widths of 100 and 200 msecs.

Figure 18 on page 42 also compares the percent success for each code. Again, the performance advantage of the g(s) and QR codes degrades beyond a 40 msec burst to the 100 msec burst. Figure 19 on page 43 shows the performance trends as burst widths lengthen. With the exception of the g(s) and QRC, all codes achieve less than 50% success at burst widths greater than or equal to 40 msec.

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16 More analysis would needed to reach a decisive conclusion.

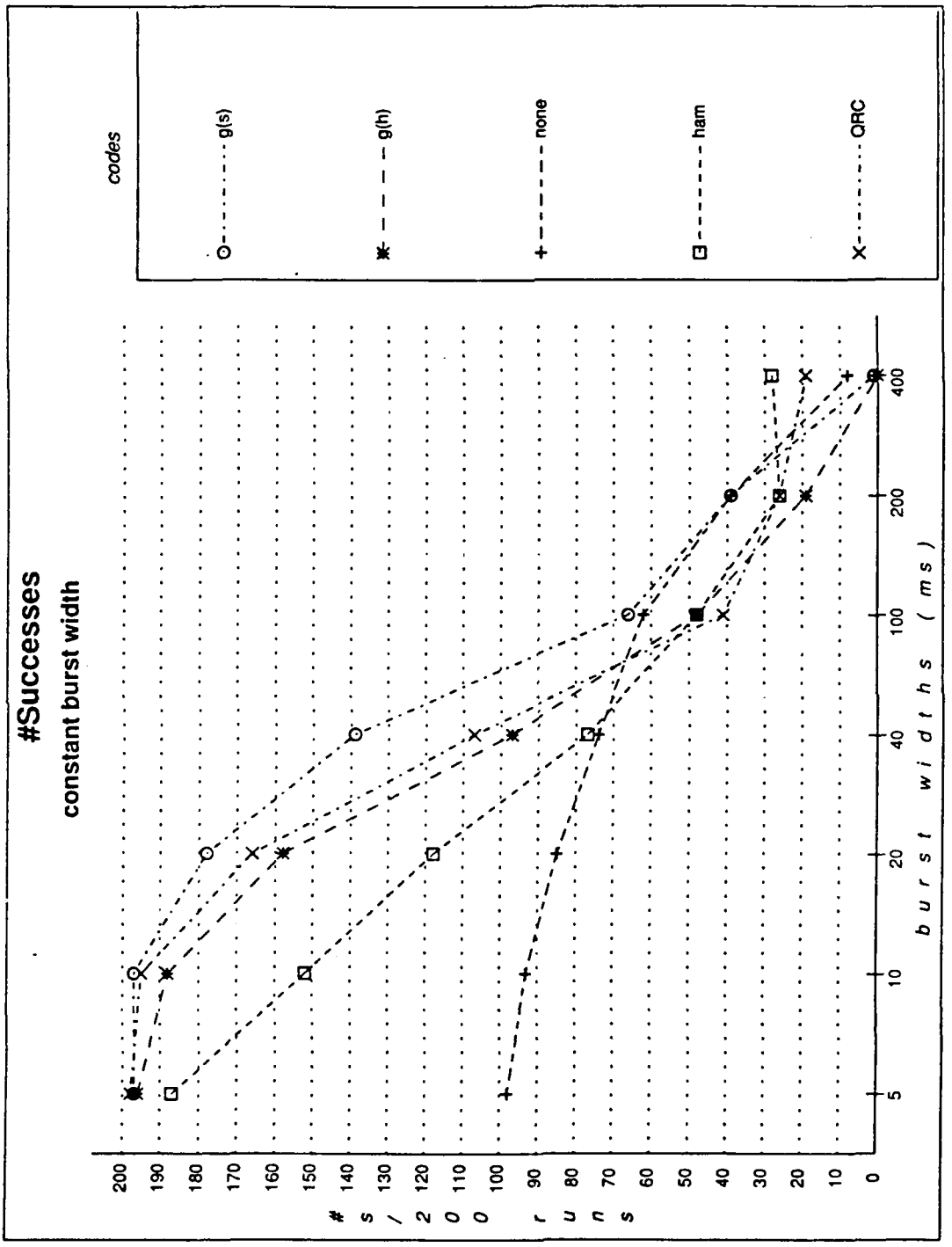

Figure 17. Constant Burst Width - S/F (line graph)

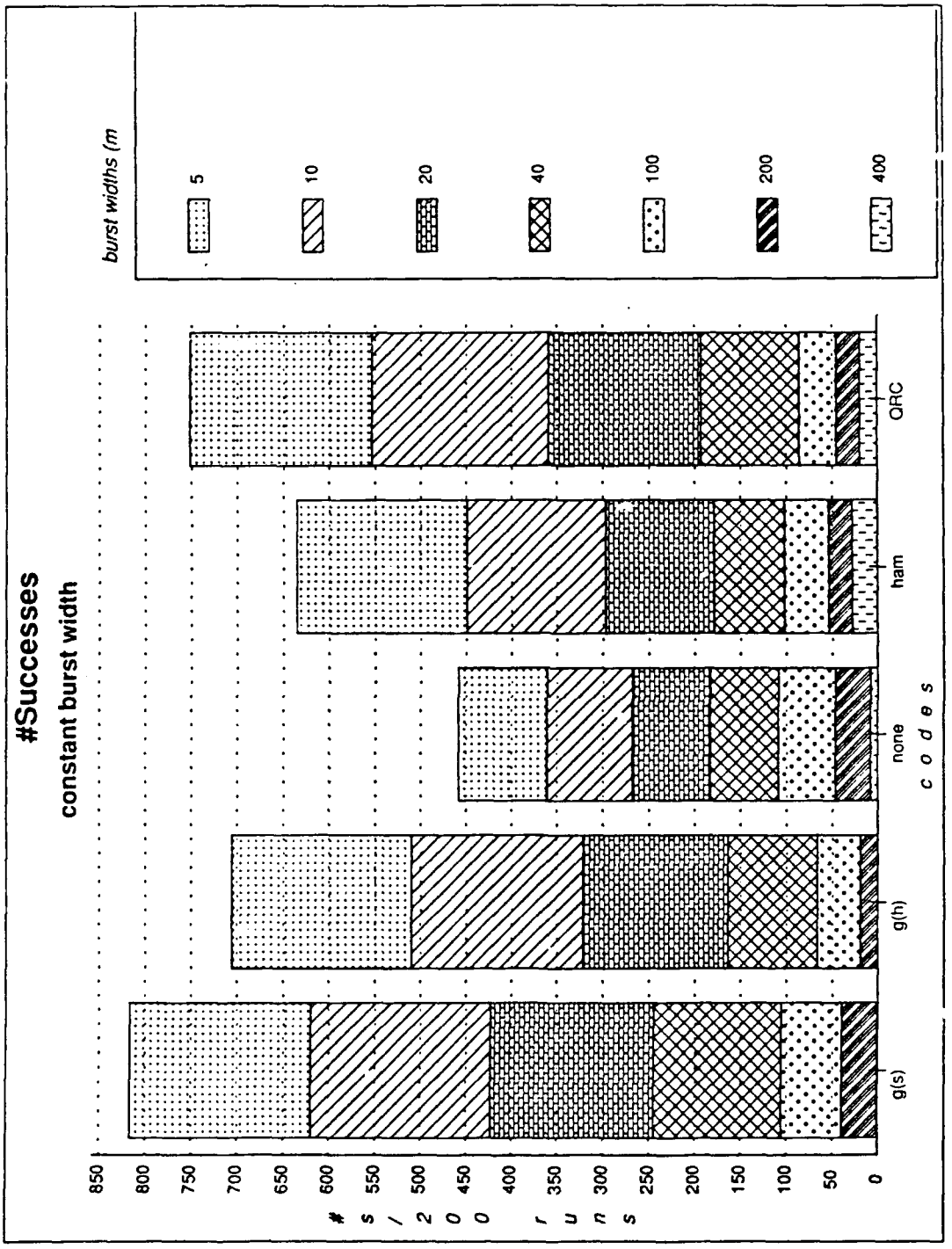

Figure 18. Constant Burst Width - S/F (bar chart)

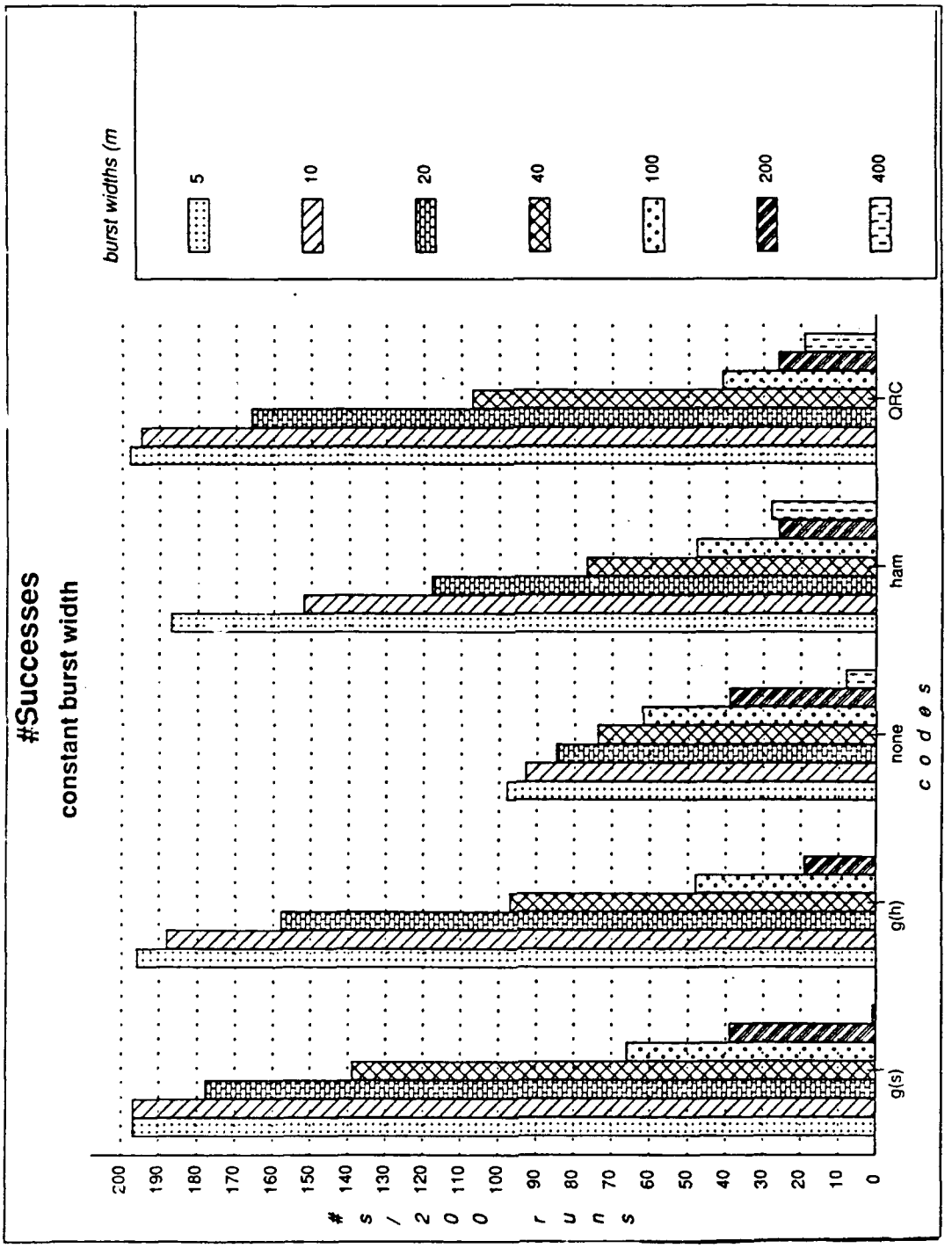

Figure 19. Constant Burst Width - S/F (comparison)

D. COMPARISON OF ERROR POSSIBILITIES

Given the larger codeword, by probablistic calculations, the QRC leads in error correction capability since there are a greater number of possible errors corrected. See Figure 20 on page 45 for an understanding of the possibilty of 6 errors corrected out of 48 bits for each code. Notice that the Golay calculation considers the hard decision number of possible errors only. The soft-decision Golay code yielded a 5% better success rate for the INMARSAT channel (see Table 6 page 28). It was also observed that the number of possible errors corrected is much closer to the QRC calcution - up to seven errors can be corrected per codeword.

In Chapter VI, the preceeding results will be summarized and recommendations presented.

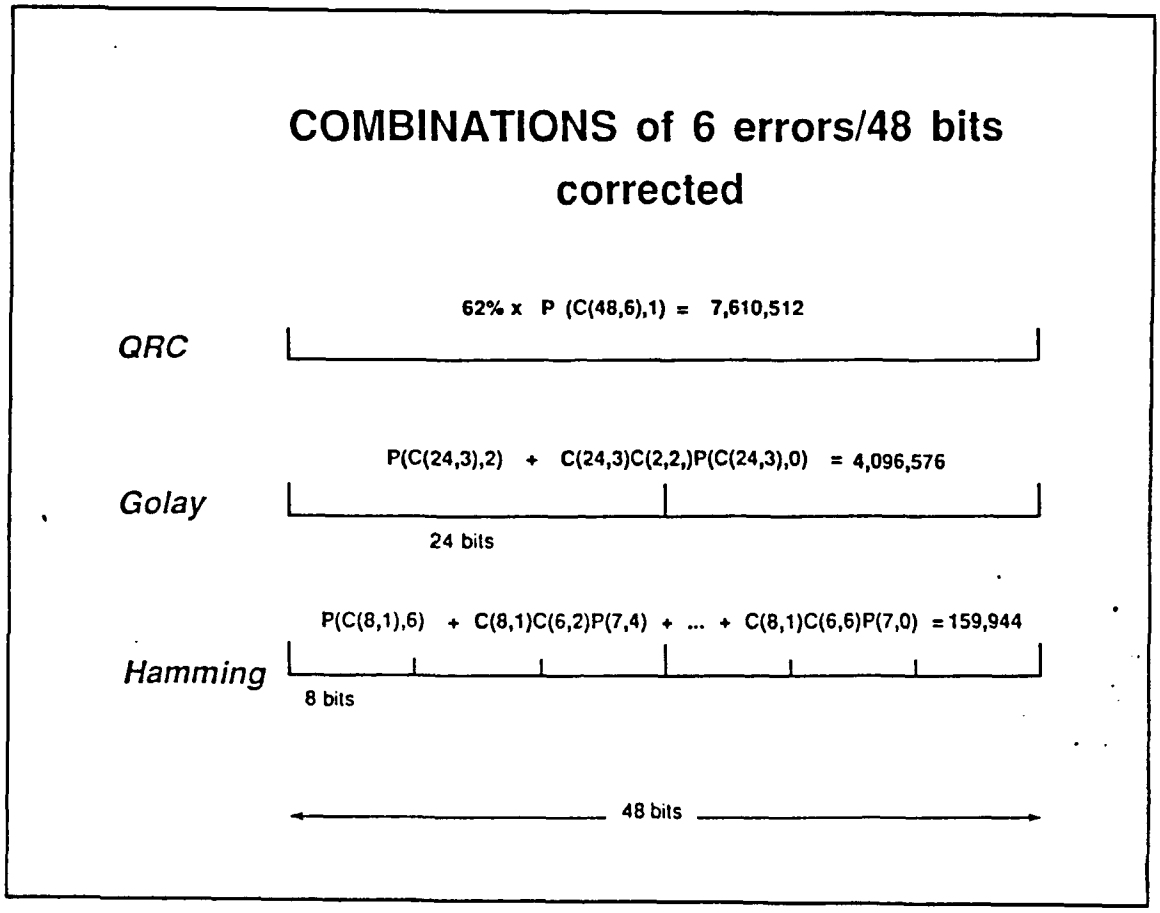

Figure 20. Possible Errors Corrected

VI. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

A. CONCLUSIONS

Three simulated noise channels -- INMARSAT random burst, AWGN, and constant burst -- were used to analyze four EDAC codes; Golay hard decision, Golay soft decision, Hamming and QRC. Before the study commenced, the INMARSAT random burst channel model was determined to be the most realistic type of LMR noise channel. It was believed by NSA that the soft Golay and QRC codes would be very close perfomance competitors. The results obtained show that the soft decision Golay slightly outperforms the QRC based on the following:

- For the Gaussian channel, the BER exponent for the g(s) is significantly less than that of the QRC at S/N of 5 dB and below. The g(s) code also had greater percentage of successful runs than the QRC for S/N levels from 2-4 dB.
- For the Constant Burst Width channel, the g(s) marginally outperforms the QRC when subjected to 10 msec burst noise. For each code, percentage of successful runs is similar at this burst width; the g(s) achieves 1% greater success. Over all burst widths, the g(s) achieves 4.9% more successful superframe runs.
- For the INMARSAT random burst channel the results are very close. The QRC outperformed the g(s) by detecting and correcting 1.5% more errors and running almost 1% more successful superframes. For the additional 1000 superframe runs, the results are even closer. Since the performance margin is so close, the conclusion is that there is no significant difference between the two codes for this simulation. More superframe runs may further support this conclusion.

The margin of performance is very close, as expected, between the soft decision Golay and the QRC. The biggest disadvantage in QRC implementation versus soft decision Golay is the difficulty of algorithmic implementation and the larger number of codeword and parity combinations to chose from. This translates into greater processing time and greater memory storage.

Based on these two considerations, soft decision Golay is recommended as the best code for FS 1024.

B. RECOMMENDATIONS FOR FURTHER STUDY

1. Study Continuation

From experience it was learned that a more concentrated level of effort should have been paid to the 10-40 msec burst width region (95% of the burst fades for the INMARSAT PDF). More superframes should be subjected to these burst widths to provide more conclusive findings.

Also, additional INMARSAT channel iterations along with a statistical analysis[17] may shed light on the difference that the long burst widths may have on the performance of the g(s) versus the QRC.

2. Implementation

Another consideration and topic for further study is the feasibility and architecture of hardware implementation of candidate EDAC algorithms. Several Digital Signal Proccessor (DSP) Integrated Circuits (ICs), such as the DSP32C and the TMS320C30, are being considered for hardware implementation. Microprocessor (assembly language) code of the soft decision Golay is already under development at DIRNSA.[18] Since the QRC codebook is much larger than the soft decision Golay, IC memory (itself limited by chip size) may be a limiting factor for hardware implementation of the QRC.

3. Other Codes

The scope of the thesis was narrowed to the four block codes; however, other possibilities should be considered in future studies. Simulation and testing of convolutional, other linear block, and concatenated codes may result in the discovery of an even better code for LMR application. A comparison of appropriate tradeoffs -- such as processing time, difficulty of algorithmic implementa-

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17 The program must be modified to obtain the necessary statistical information, such as - the bit position of the error, position of the fade, the number of errors each fade caused, etc.

18 This EDAC was chosen as the code to protect the digitized voice (CELP processed) information bits.

tion, and code performance -- should be weighed in order to fairly judge the best code for the MI bits.

APPENDIX A: FORTRAN CODE

A. MAIN DRIVER

```
c  14*240=3360 bits per superframe (sf)
c 72+72=144 bits per mi
c 3360-144=3216 bits of fill per sf
c 3360/2=1680 bauds per sf

c*****************************************************************
c     This program generates a superframme of 3360 bits.
c     72 bits are of interest in the detection and correction
c     of errors.  Three different EDAC schemes simmulated here
c     for comparison of the best scheme under various conditions.
c     The three codes are Golay (24,12) using soft and hard
c     decision logic, Hamming (8,4), and Quadradic Residue Code
c     (QRC)(48,24).  Also, a run with no coding is performed as
c     a control case.

c     The entire superframe is interleaved, transmitted over a
c     simulated AWGN channel, received, deinterleaved, and
c     finally - checked for errors.  The run in considered a
c     failure if there are ANY errors.

c     Options for the simmulated channel include variance of the
c     s/n during non-fade (the fade s/n was held at -24.0 dB), and
c     two burst modes.  The first burst mode used the INMARSAT
c     values of varying length from 10-200ms for LMR.  The second
c     burst mode allows for a constant burst length input.
c*****************************************************************

        program mainedac

c****************Declarations*************************************

        integer*4 tbaud(1680)
        integer*4 fillbits(3216)
        integer*4 parity(72)
        integer*4 rbaud(1680)
        integer*4 rbcnt,tbcnt,decodcnt1,decodcnt2
        integer*4 modegolay,ham,parnum,qrc,sf,nummi
        integer*4 index,prevoutdibit,table(16)
```

```
      integer*4 tbits,bits,txbits,rbits
      real xdisp,ydisp,confh,confl
      real samples(3),noise,noisef,bprob,probq
      integer*4 mode,iseed,vary
      integer*4 testcnt,tbit(3360),rbit(3360),intlvtable(144)
      integer*4 mibits(72),codeword(8),hmatrix(8),syndrometable(8)
      integer*4 testcnt,paritybit
      real intlvconf(3360),rcodeconf(144),rhashconf(144)
      real rfillconf(3216)
      real conf(24),gaus(256)
      integer*4 code(144),hashcode(144),qrcbits(144),hambits(72)
      integer*4 hashtable(144)
      integer*4 rcode(144)
      integer*4 itoterr,qrccwerr,qrcsferr,bwidth,myerror,hamerr
      integer*4 iallerr, itotbitct
      logical insync
      integer*4 success,bits,fail,nerror,intlvrcnt,ifillrcnt,ihashrcnt
      integer*4 rhashcode(144),rfillbits(3216)
      integer*4 isym(2047)
      integer*4 idata(24),kdata(24),ierr(5),qdata(48),hdata(4)
      common /blk5/idata
      common /blk7/conf,isym,kdata,ierr

c******************DATA and TABLES************************************

      myerror = 0
      data init,initfill /1,1/
      data table /2,0,3,1,3,2,1,0,0,1,2,3,1,3,0,2/
      if ((ham.eq.0).and.(qrc.eq.0)) then
         data hashtable /
     1     1,25,49,73,97,121,2,26,50,74,98,122,
     1     3,27,51,75,99,123,4,28,52,76,100,124,
     1     5,29,53,77,101,125,6,30,54,78,102,126,
     1     7,31,55,79,103,127,8,32,56,80,104,128,
     1     9,33,57,81,105,129,10,34,58,82,106,130,
     1     11,35,59,83,107,131,12,36,60,84,108,132,
     1     13,37,60,85,109,133,
     1     14,38,61,86,110,134,
     1     15,39,62,87,111,135,
     1     16,40,63,88,112,136,
     1     17,41,64,89,113,137,
     1     18,42,65,90,114,138,
     1     19,43,66,91,115,139,
     1     20,44,67,92,116,140,
     1     21,45,68,93,117,141,
```

```
     1       22,46,69,94,118,142,
     1       23,47,70,95,119,143,
     1       24,48,71,96,120,144/
          end if

          if (qrc.eq.1) then
             data hashtable /
     1         1,49,97,2,50,98,3,51,99,4,52,100,
     1         5,53,101,6,54,102,7,55,103,8,56,104,
     1         9,57,105,10,58,106,11,59,107,12,60,108,
     1         13,61,109,14,62,110,15,63,111,16,64,112,
     1         17,65,113,18,66,114,19,67,115,20,68,116,
     1         21,69,117,22,70,118,23,71,119,24,72,120,
     1         25,73,121,26,74,122,27,75,123,28,76,124,
     1         29,77,125,30,78,126,31,79,127,32,80,128,
     1         33,81,129,34,82,130,35,83,131,36,84,132,
     1         37,85,133,38,86,134,39,87,135,40,88,136,
     1         41,89,137,42,90,138,43,91,139,44,92,140,
     1         45,93,141,46,94,142,47,95,143,48,96,144/
          end if

          if (ham.eq.1) then
             data hashtable /
     1         1,9,17,25,33,41,49,57,65,73,81,89,97,105,113,121,129,137,
     1         2,10,18,26,34,42,50,58,66,74,82,90,98,106,114,122,130,138,
     1         3,11,19,27,35,43,51,59,67,75,83,91,99,107,115,123,131,139,
     1         4,12,20,28,36,44,52,60,68,76,84,92,100,108,116,124,132,140,
     1         5,13,21,29,37,45,53,61,69,77,85,93,101,109,117,125,133,141,
     1         6,14,22,30,38,46,54,62,70,78,86,94,102,110,118,126,134,142,
     1         7,15,23,31,29,47,55,63,71,79,87,95,103,111,119,127,135,143,
     1         8,16,24,32,30,47,56,64,72,80,88,96,104,112,120,128,136,144/
          end if

c         read in table for golay decoder from disk file

          open (3,file='isytab.dat',status='old',form='formatted')
          read (3,20)isym
20        format(10(I6))
          close(3)

c         read in gaussian distribution from disk file

          open (4,file='gaussian.dat',status='old',form='formatted')
          read (4,25)gaus
25        format(8(f6.0,1x))
```

```
      close(4)

c************Interactive Input*****************************************

      write(6,*)'how many 420ms superframes would you like to run?'
      read(5,*) sf
      write(6,*)'what golay mode ? (1=soft,2=hard,3=nogolay) = ?'
      read (5,*) modegolay
      if(modegolay.eq.3)then
         write(6,*)'would you like to try the Hamming code?
     *(1=yes,0=no) . . .'
         read(5,*) ham
         if(ham.eq.1) qrc=0
         if(ham.eq.0) then
            write(6,*)'would you like to perform a QRC error count?
     *(1=yes,0=no) . . . '
            read(5,*) qrc
         end if
      else
         ham=0
         qrc=0
      end if
      write(6,*) 'what is s/n ratio in dB during fade = ? (real #)'
c                should be -24dB
      read (5,*) noisef
      write(6,*) 'what is s/n ratio in dB during no fade = ? (real #)'
      read (5,*) noise
      write(6,*) 'what is mode ? (0 for non-fading, 1 for fading) = '
      read (5,*) mode
      if(mode.eq.1)then
         write(6,*)'what is the time seed? (any positive integer) = '
         read (5,*) iseed
         write(6,*)'would you like to vary burst prob and width?
     *(1=yes,0=no) . . . '
         read (5,*) vary
         if(vary.eq.1) then
            write(6,*)'what burst prob?(r .94056 INMARSAT) = '
            read (5,*) bprob
            write(6,*)'what burst width?(i 120=10ms, INMARSAT) = '
            read (5,*) bwidth
         end if
      else
         iseed = 1
      end if
```

```
c****** write the superframe interleave table for the 144 codeword bits
c****** only throughout frames 4 through 14 (frame 4 starts at bit 721)

        do 35 m=1,9
           do 30 mm=1,8
              intlvtable(((m-1)*16)+((mm-1)*2)+1)=
     1                          721+((m-1)*240)+((mm-1)*30)
              intlvtable(((m-1)*16)+((mm-1)*2)+2)=
     1                          721+((m-1)*240)+(((mm-1)*30)+10)
30         continue
35      continue

c*********** Initialize ************************************************

        itoterr = 0
        qrcsferr = 0
        qrccwcnt = 0
        success = 0
        fail = 0
        ifirst=1
        tbcnt=1680
        rbcnt=1680-10

c***** Begin for sf# of superframes*****************************************
c***** don't start counting results until n=about 3 so that error counters
c***** are in sync (test if insync and insyncfill .eq..true)

do 500 n=1,sf
c                loop for 1680 baud/sf - generate, tx, sim, rcv, etc.
   do 400 mk=1,1680
      tbcnt=tbcnt+1
      if(tbcnt.eq.1681)then
         tbcnt=1

c***** fill mibits
                if(qrc.eq.1)nummi=72
                if(qrc.eq.0)nummi=36
         do 40 m=1,nummi
            call bitgen11(2,init,tbits)
                   init=0
                   if((qrc.eq.0).and.(ham.eq.0)) then
                      mibits(((m-1)*2)+1)=0
                      mibits(((m-1)*2)+2)=0
                      if((tbits.eq.1).or.(tbits.eq.3))then
                         mibits(((m-1)*2)+1)=1
```

```
                        end if
                        if((tbits.eq.2).or.(tbits.eq.3))then
                           mibits(((m-1)*2)+2)=1
                        end if
                     end if
                     if(ham.eq.1) then
                        hambits(((m-1)*2)+1)=0
                        hambits(((m-1)*2)+2)=0
                        if((tbits.eq.1).or.(tbits.eq.3))then
                           hambits(((m-1)*2)+1)=1
                        end if
                        if((tbits.eq.2).or.(tbits.eq.3))then
                           hambits(((m-1)*2)+2)=1
                        end if
                     end if
                     if(qrc.eq.1) then
                        qrcbits(((m-1)*2)+1)=0
                        qrcbits(((m-1)*2)+2)=0
                        if((tbits.eq.1).or.(tbits.eq.3))then
                           qrcbits(((m-1)*2)+1)=1
                        end if
                        if((tbits.eq.2).or.(tbits.eq.3))then
                           qrcbits(((m-1)*2)+2)=1
                        end if
                     end if
40                continue
                  if (qrc.eq.1) go to 95

c***** fill parbits
                  if (ham.eq.1) parnum=18
                  if ((ham.eq.0).and.(qrc.eq.0)) parnum=6
                  call matrixgen(8,4,hmatrix,syndrometable)

          do 70 m=1,parnum
c***** bit encoder for hamming
                     if(ham.eq.1)then
                        do 48 mm=1,2
                           codeword(((mm-1)*2)+1)=hambits(((m-1)*4)
     1                           +(((mm-1)*2)+1))
                           codeword(((mm-1)*2)+2)=hambits(((m-1)*4)
     1                           +(((mm-1)*2)+2))
c                           codeword(((mm-1)*2)+5)=0
c                           codeword(((mm-1)*2)+6)=0
48                         continue
                           call encodeham(8,4,hmatrix,paritybit,codeword)
```

```
c***** load hamming codewords (parity + data) ********************
                        do 50 mm=1,8
                           code(((m-1)*8)+mm)=codeword(mm)
50                         continue
                        else
c***** generate parity bauds for golay here
                        if (qrc.eq.0)then
                           do 55 mm=1,6
                              idata(((mm-1)*2)+1)=mibits(((m-1)*12)
     1                              +(((mm-1)*2)+1))
                              idata(((mm-1)*2)+2)=mibits(((m-1)*12)
     1                              +(((mm-1)*2)+2))
55                         continue
                        end if

                        call golenc

                        do 60 mm=1,12
                           parity(((m-1)*12)+mm)=idata(12+mm)
60                         continue
                     end if
70                continue

c***** load Golay and QRC  codewords (bits)**************************
                  if((ham.eq.0).and.(qrc.eq.0)) then
                     do 90 m=1,6
                        do 80 mm=1,12
                           code(((m-1)*24)+mm)=mibits(((m-1)*12)+mm)
                           code(((m-1)*24)+mm+12)=parity(((m-1)*12)+mm)
80                         continue
90                      continue
                  end if
95                continue
                  if(qrc.eq.1) then
                     do 97 m=1,144
                           code(m)=qrcbits(m)
97                      continue
                  end if

c***** scramble the codewords
                  do 100 m=1,144
                     hashcode(m)=code(hashtable(m))
100               continue
                  do 110 m=1,1608
```

```
c                  get the rest of the superframe's bits
                   call bitgen11fill(2,initfill,tbits)
c                  same as bitgen11 but a separate routine

                   initfill=0
                   fillbits(((m-1)*2)+1)=0
                   fillbits(((m-1)*2)+2)=0
                   if((tbits.eq.1).or.(tbits.eq.3))then
                      fillbits(((m-1)*2)+1)=1
                   end if
                   if((tbits.eq.2).or.(tbits.eq.3))then
                      fillbits(((m-1)*2)+2)=1
                   end if
110             continue

c***** load the superframe with codewords and fill
                intlvcnt=1
                ihashcnt=1
                ifillcnt=1
                do 130 m=1,3360
                   if(m.eq.(intlvtable(intlvcnt)))then
                      tbit(m)=hashcode(ihashcnt)
                      ihashcnt=ihashcnt+1
                      intlvcnt=intlvcnt+1
                   else
                      tbit(m)=fillbits(ifillcnt)
                      ifillcnt=ifillcnt+1
                   end if
130             continue

c***** bits to bauds
                do 140 m=1,1680
                   if(tbit(((m-1)*2)+1).eq.0)then
                      if(tbit(((m-1)*2)+2).eq.0)tbaud(m)=0
                      if(tbit(((m-1)*2)+2).eq.1)tbaud(m)=2
                   else
                      if(tbit(((m-1)*2)+2).eq.0)tbaud(m)=1
                      if(tbit(((m-1)*2)+2).eq.1)tbaud(m)=3
                   end if
140             continue
             end if

             txbits=tbaud(mk)

c***** differential phase encoding
```

```
                index=(4*txbits)+prevoutdibit
                txbits=table(index+1)
                prevoutdibit=txbits

c***** transmit over simulated channel and receive
                call tx(txbits,samples)
                if(vary.eq.1)then
                   call chsim(samples,noise,noisef,mode,iseed,gaus,
     1                        bprob,bwidth)
                else
                   call sim(samples,noise,noisef,mode,iseed,gaus,n,sf,mk)
                end if
                call rcv(samples,rbits,xdisp,ydisp,confh,confl)

c***** The confidence calculations are used for softgolay only *****
                rbcnt=rbcnt+1
                rbaud(rbcnt-1)=rbits
                intlvconf(((rbcnt-2)*2)+1)=confl
                intlvconf(((rbcnt-2)*2)+2)=confh
      if (rbcnt.eq.1681) then
                   testcnt=testcnt+1
           rbcnt=1
           if (ifirst.eq.1) then
              ifirst=0
           else

c***** unpack and decode the bits and count any errors in the mi
c       this would be 18 calls to hamming or 6 calls to golay
c       if any of the 72 mi bits are in error then we fail and
c***** bauds to bits
                      do 150 m=1,1680
                         rbit(((m-1)*2)+1)=0
                         rbit(((m-1)*2)+2)=0
                         if((rbaud(m).eq.1).or.(rbaud(m).eq.3))
     1                      rbit(((m-1)*2)+1)=1
                         if((rbaud(m).eq.2).or.(rbaud(m).eq.3))
     1                      rbit(((m-1)*2)+2)=1
150                   continue

c***** deinterleave bits from the superframe
                      intlvrcnt=1
                      ihashrcnt=1
                      ifillrcnt=1
                      do 160 m=1,3360
                         if(m.eq.(intlvtable(intlvrcnt)))then
```

```
                        rhashcode(ihashrcnt)=rbit(m)
                        rhashconf(ihashrcnt)=intlvconf(m)
                        ihashrcnt=ihashrcnt+1
                        intlvrcnt=intlvrcnt+1
                     else
                        rfillbits(ifillrcnt)=rbit(m)
                        rfillconf(ifillrcnt)=intlvconf(m)
                        ifillrcnt=ifillrcnt+1
                     end if
160                  continue

c***** descramble the codeword bits
                     do 170 m=1,144
                        rcode(hashtable(m))=rhashcode(m)
                        rcodeconf(hashtable(m))=rhashconf(m)
170                  continue

c***** decode the codewords (baud) ****************************
                     if(qrc.eq.1)then
                        decodcnt1=3
                        decodcnt2=24
                     end if
                     if(ham.eq.1)then
                        decodcnt1=18
                        decodcnt2=2
                     end if
                     if((qrc.eq.0).and.(ham.eq.0))then
                        decodcnt1=6
                        decodcnt2=6
                     end if
                     do 200 m=1,decodcnt1
                        if((ham.eq.0).and.(qrc.eq.0))then
                           do 180 mm=1,24
                              idata(mm)=rcode(((m-1)*24)+mm)
                              conf(mm)=rcodeconf(((m-1)*24)+mm)
180                        continue
                        end if
                        if(ham.eq.1)then
                           do 181 mm=1,8
                              codeword(mm)=rcode(((m-1)*8)+mm)
181                        continue

                        end if
                        if(qrc.eq.1)then
                           do 182 mm=1,48
```

```
                              qdata(mm)=rcode(((m-1)*48)+mm)
182                        continue
                        end if

                        if(modegolay.eq.1)call soft
                        if(modegolay.eq.2)call hard
                        if(ham.eq.1)then
                           call decodeham(8,4,paritybit,myerror,hmatrix,
     &                                    syndrometable,codeword)

c***** strip off the first 4 bits of each codeword MI bits.**********0
                           do 183 mm=1,4
                              hdata(mm)=codeword(mm)
183                        continue

                           if(myerror.eq.1)then
                              hamerr = hamerr + 2
                              write(6,*)'decodeham detected errors '
                           end if
                        end if

c***** count errors in 72 MI bits (golay=12/24,hamming=4/8)
c                  or all 144 bits (qrc=48/48)
c***** before the errors are counted they are changed to baud
c*****************************************************************
                        qrccwerr=0
                        do 190 k=1,decodcnt2
                           if((qrc.eq.0).and.(ham.eq.0))then
                              if(idata(((k-1)*2)+1).eq.0)then
                                 if(idata(((k-1)*2)+2).eq.0)bits=0
                                 if(idata(((k-1)*2)+2).eq.1)bits=2
                              else
                                 if(idata(((k-1)*2)+2).eq.0)bits=1
                                 if(idata(((k-1)*2)+2).eq.1)bits=3
                              end if
                           end if
                           if(ham.eq.1)then
                              if(hdata(((k-1)*2)+1).eq.0)then
                                 if(hdata(((k-1)*2)+2).eq.0)bits=0
                                 if(hdata(((k-1)*2)+2).eq.1)bits=2
                              else
                                 if(hdata(((k-1)*2)+2).eq.0)bits=1
                                 if(hdata(((k-1)*2)+2).eq.1)bits=3
                              end if
                           End if
```

```
                        if(qrc.eq.1)then
                           if(qdata(((k-1)*2)+1).eq.0)then
                              if(qdata(((k-1)*2)+2).eq.0)bits=0
                              if(qdata(((k-1)*2)+2).eq.1)bits=2
                           else
                              if(qdata(((k-1)*2)+2).eq.0)bits=1
                              if(qdata(((k-1)*2)+2).eq.1)bits=3
                           end if
                        end if
                        call biterr11a(bits,2,insync,nerror)
                        itoterr=itoterr+nerror
                        if(qrc.eq.1)qrccwerr=qrccwerr+nerror
190                  continue

c***** This is the QRC BER counter section ***************************
c       errors/codeword are checked (for decodcnt1=3 cws)
c       QRC(48,24) will correct 5 errors/cw and 62.02% of the 6th errors
c*********************************************************************
                     if(qrc.eq.1) then
                        if(qrccwerr.eq.0)then
                           write(6,*)'there were no errors in QRC cw'
                        end if
                        if((qrccwerr.le.5).and.(qrccwerr.gt.0)) then
                           write(6,*)'# errors corrected = ',qrccwerr
                           qrccwerr=0
                        end if
                        if(qrccwerr.eq.6)then
                           probq = rand(0)
                           if(probq.le..6202)then
                              write(6,*)'qrc 6th error corrected'
                              qrccwerr=0
                           end if
                        end if
                     qrcsferr=qrccwerr+qrcsferr
                     end if
195                  continue
200               continue

c***** print error results
c       if any errors in total error count , the run is a failure
c*********************************************************************
                  if(qrc.eq.1) then
                     itoterr = qrcsferr
                     iallerr = iallerr + qrcsferr
                     itotbitct = itotbitct + 144
```

```
                    end if
                    if(itoterr.eq.0)then
                       success=success+1
                       write(6,*)'success = ',success
                    end if
                    if(itoterr.ne.0)then
                       fail=fail+1
                       write(6,*)'fail = ',fail
                       write(6,*)'total errors in sf = ',itoterr
                    end if

c***** reinitialize for new superframe ************************
                    qrcsferr=0
                    itoterr=0
                    hamerr=0
                    if(.not.insync)then
                       fail=0
                       success=0
                       testcnt=0
                       itotbitct=0
                       iallerr=0
                    end if

c***** or use the fill bits to measure ber in non-fading noise
c                   call biterr11afill(bit,2,insyncfill,nerror)

                 end if
              end if
400        continue
           write(6,*) ' you just completed superframe # ',n
           if((qrc.eq.1).and.(mod(n,50).eq.0))write(6,*)
     1       'iallerr= ',iallerr,' itotbitct= ',itotbitct,
     1       'n = ',n
500     continue

c***** print final counts and results
        write(6,*)' the total number of failures = ',fail
        write(6,*)' the total number of successes = ',success
        if(modegolay.eq.1) write(6,*)' This was a soft golay run'
        if(modegolay.eq.2) write(6,*)' This was a hard golay run'
        if(modegolay.eq.3) write(6,*)' This was a nogolay run'
        if(ham.eq.1)write(6,*)' This was a Hamming run'
        if(qrc.eq.1)write(6,*)' This was a QRC BE  ount run'
        write(6,*)' This run used fading (1=yes,0=no) ',mode
        if(vary.eq.1)write(6,*)'fading width, bwidth = ',bwidth
```

```
        write(6,*)' s/n during fade (dB) = ',noisef
        write(6,*)' s/n during non-fade (dB) = ',noise

c*****QUIT!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
        end
```

B. SUBROUTINES

```
c*************************************************************

        subroutine biterr11a(data,nbits,insync,nerror)

        integer*4 data, nbits, nerror, rxdata, shindex, error
        integer*4 index, errcnt, bitcnt, i, itemp
integer*4 nblck, btest, lshift, rshift, xor
        logical insync
        data errcnt, bitcnt / 0, 0 /
        data rxdata, index / 0, 1 /
data nblck /100/

        rxdata = rshift(rxdata,nbits)
        call mvbits(data,0,nbits,rxdata,11-nbits)

        shindex = lshift(index,2)
        itemp = xor(index,shindex)
        index = rshift(index,nbits)
        call mvbits(itemp,2,nbits,index,11-nbits)

        nerror = 0
        error = xor(index,rxdata)
        if (error .ne. 0) then
           do 9 i =11-nbits, 10
              if (btest(error,i).eq.1) nerror = nerror +1
9          continue
        end if

        errcnt = errcnt + nerror
        bitcnt = bitcnt + nbits

        if (insync) then
           if (bitcnt .ge. nblck) then
              if (float(errcnt) .gt. .35 * float(bitcnt)) then
                 insync = .false.
         nblck=100
              else
 write(6,*) 'errors in ',nblck, ' bits = ', errcnt
         nblck=3000
c                to span fades
                 errcnt = 0
                 bitcnt = 0
              end if
```

```
            end if
         end if

         if (.not. insync) then
            if (bitcnt .ge. 20) then
               if (float(errcnt) .le. .2 * float(bitcnt)) then
                  insync = .true.
          write(6,*) 'insync = true'
               else
          if (bitcnt.eq.20) write(6,*) 'not yet in sync'
                  index = rxdata
                  if (index .eq. 0) index = 1
               end if
               errcnt = 0
               bitcnt = 0
            end if
         end if

         return
         end
c-------------------------------------------------------------------------------

         subroutine biterr11afill(data,nbits,insync,nerror)

         integer*4 data, nbits, nerror, rxdata, shindex, error
         integer*4 index, errcnt, bitcnt, i, itemp
integer*4 nblck, btest, lshift, rshift, xor
         logical insync
         data errcnt, bitcnt / 0, 0 /
         data rxdata, index / 0, 1 /
data nblck /100/

         rxdata = rshift(rxdata,nbits)
         call mvbits(data,0,nbits,rxdata,11-nbits)

         shindex = lshift(index,2)
         itemp = xor(index,shindex)
         index = rshift(index,nbits)
         call mvbits(itemp,2,nbits,index,11-nbits)

         nerror = 0
         error = xor(index,rxdata)
         if (error .ne. 0) then
            do 11 i =11-nbits, 10
               if (btest(error,i).ne.0) nerror = nerror +1
```

```
11          continue
         end if

         errcnt = errcnt + nerror
         bitcnt = bitcnt + nbits

         if (insync) then
            if (bitcnt .ge. nblck) then
               if (float(errcnt) .gt. .35 * float(bitcnt)) then
                  insync = .false.
          nblck=100
               else
 write(6,*) 'errors in ',nblck, ' bits = ', errcnt
          nblck=3000
c                 to span fades
                  errcnt = 0
                  bitcnt = 0
               end if
            end if
         end if

         if (.not. insync) then
            if (bitcnt .ge. 20) then
               if (float(errcnt) .le. .2 * float(bitcnt)) then
                  insync = .true.
           write(6,*) 'insync = true'
               else
           if (bitcnt.eq.20) write(6,*) 'not yet in sync'
                  index = rxdata
                  if (index .eq. 0) index = 1
               end if
               errcnt = 0
               bitcnt = 0
            end if
         end if

         return
         end

c*************************************************************************

         function btest(i1,i2)

C ***    this function returns 1 if bit position a2 of a1 is 1 and
c ***                  returns 0 if bit position a2 of a1 is 0
```

```
        integer*4 t1,t2,btest,i1,i2

        t1=i1
        t2=i2
        t1 = rshift(t1,t2)
        t1 = and(t1,1)
        btest = t1

        return
        end

C*********************************************************************


        subroutine mvbits(isource,ibitfrom,length,idest,ibitto)

        integer*4 isource, ibitfrom, length, idest, ibitto, n
        integer*4 k, ks, btest, xor, lshift

        do 12 n = 1, length

           k = ibitto + n - 1
           ks = lshift(1,k)

           if (btest(isource,(ibitfrom+n-1)).ne.0) then
c **set**
              if (btest(idest,k).eq.0)
     1            idest = xor(idest,ks)
c **clear**
           else
              if (btest(idest,k).ne.0)
     1            idest = xor(idest,ks)
           end if
12      continue

        return
        end

c---------------------------------------------------------------------

c       soft decision decoder for golay(24,12)
c      uses chase ii algorithm with table look-up decoder

        subroutine soft
```

```
      common/blk5/idata
      common/blk7/conf,isym,kdata,ierr
      integer*4 idata(24),kdata(24),ierr(5)
       integer*4 isym(2047)
      integer*4 nb(4),mask(4,24),jb(16,24),ib(24),nerr
       real conf(24)

      nerr=1
C
C

c      w is analog weight of most likely error pattern
c      set w initially to a very large value
       w=1000000.0

c      identify 4 bits with lowest confidence values
       call low4(nb)
       wgt4=0.

c      gen 4 masks identifying 4 bits
       call mgen(mask,nb)

c      gen 2**4=16 patterns
       call patgen(mask,jb)

c      test each of 16 patterns for the SOFT decoder
       do 19 i=1,16

c         clear ierr
          do 13 j=1,5
             ierr(j)=0
13        continue

c         add data and test error pattern, store in kdata
          do 14 j=1,24
             call exor(kdata(j),idata(j),jb(i,j))
14       continue

c         binary decoder
c         accepts input data in kdata
c         returns data uncorrected
c         returns no. of errors in ierr(5)
c         returns location of errors in ierr(1) to ierr(4)
```

```
          call golay

c         test if decoded word was error free
          if (ierr(5).eq.0) then
c            test word was error free
c            accept test word as best estimate
             w=0.0

             do 15 j=1,24
                idata(j)=kdata(j)
15           continue
      return
   else
c            test word contained errors
c            get final error pattern, calculate its analog wgt
             wgt=0.0
             n=ierr(5)

c            add detected errors to test error  pattern
             do 16 j=1,n
                ix=ierr(j)
                call exor(jb(i,ix),jb(i,ix),nerr)
16          continue

             do 17 j=1,24
                if(jb(i,j).eq.1)wgt=wgt+conf(j)
17           continue

c            compare wgt and w
c            save error pattern with lowest analog weight

             if(wgt.lt.w)then
c               store new value
c               save error pattern
                w=wgt
                do 18 j=1,24
                   ib(j)=jb(i,j)
18              continue
      end if
   end if
19   continue

c       decode data with most likely error pattern
        do 21 i=1,24
           call exor(idata(i),idata(i),ib(i))
```

```
21      continue

        return
        end

c-------------------------------------------------------------------------------

c      hard decision decoder for golay(24,12)
c     uses chase ii algorithm with table look-up decoder

        subroutine hard

        integer*4 idata(24),kdata(24),ierr(5)
         integer*4 isym(2047)
        integer*4 nb(4),mask(4,24),jb(16,24),ib(24),nerr
         real conf(24)
        common/blk5/idata
        common/blk7/conf,isym,kdata,ierr

        nerr=1

c        w is analog weight of most likely error pattern
c        set w initially to a very large value
         w=1000000.0

c        identify 4 bits with lowest confidence values
         call low4(nb)
         wgt4=0.

c        gen 4 masks identifying 4 bits
         call mgen(mask,nb)

c        gen 2**4=16 patterns
         call patgen(mask,jb)

c        test 1 pattern --> hard
         do 28 i=1,1

c           clear ierr
            do 22 j=1,5
               ierr(j)=0
22          continue

c           add data and test error pattern, store in kdata
            do 23 j=1,24
```

```
            call exor(kdata(j),idata(j),jb(i,j))
23       continue

c          binary decoder
c          accepts input data in kdata
c          returns data uncorrected
c          returns no. of errors in ierr(5)
c          returns location of errors in ierr(1) to ierr(4)

           call golay

c          test if decoded word was error free
           if (ierr(5).eq.0) then
c             test word was error free
c             accept test word as best estimate
              w=0.0

              do 24 j=1,24
                 idata(j)=kdata(j)
24            continue
      return
   else
c             test word contained errors
c             get final error pattern, calculate its analog wgt
              wgt=0.0
              n=ierr(5)

c             add detected errors to test error  pattern
              do 25 j=1,n
                 ix=ierr(j)
                 call exor(jb(i,ix),jb(i,ix),nerr)
25          continue

              do 26 j=1,24
                 if(jb(i,j).eq.1)wgt=wgt+conf(j)
26            continue

c             compare wgt and w
c             save error pattern with lowest analog weight

              if(wgt.lt.w)then
c                store new value
c                save error pattern
                 w=wgt
                 do 27 j=1,24
```

```
                  ib(j)=jb(i,j)
27              continue
      end if
   end if
28   continue

c       decode data with most likely error pattern
        do 29 i=1,24
           call exor(idata(i),idata(i),ib(i))
29      continue

        return
        end

c-------------------------------------------------------------------------------

        subroutine low4(nb)

c       to identify in nb the location of 4 lowest conf values
        dimension d(4)
        integer*4 kdata(24),ierr(5),nb(4)
        integer*4 isym(2047)
        real conf(24)
        common/blk7/conf,isym,kdata,ierr

c       assume first 4 are lowest

        do 31 i=1,4
           d(i)=conf(i)
           nb(i)=i
31      continue

c       compare remaining values
        do 33 i=5,24
           a=conf(i)
           n=i
           j=1
           if (j.gt.4) go to 33
              if (a.lt.d(j)) then
c                a is < d(j)
c                replace d(j) with a
c                save d(j) to compare with other values in d
c                save nb(j)
                 b=d(j)
                 nx=nb(j)
```

```
c                replace
                 d(j)=a
                 nb(j)=n
c                rename the saved values
                 a=b
                 n=nx
                 j=1
              end if
c          incr j
           j=j+1
33      continue

57      return
        end

c-------------------------------------------------------------------------------

c       mask generator for soft decision golay decoder
c       generate 4 masks with 1 bit in location nb(i)

        subroutine mgen(mask,nb)

        dimension mask(4,24),nb(4)
        integer*4 mask,nb

        do 35 i=1,4
           do 34 j=1,24
              mask(i,j)=0
34         continue
           n=nb(i)
           mask(i,n)=1
35      continue

        return
        end

c-------------------------------------------------------------------------------

c       generate 16 patterns based on 4 bits

        subroutine patgen(mask,jb)

        integer*4 mask(4,24),jb(16,24)

        do 36 i=1,24
```

```
            jb(1,i)=0
            jb(2,i)=mask(1,i)
            jb(3,i)=mask(2,i)
            jb(4,i)=mask(3,i)
            jb(5,i)=mask(4,i)
            jb(6,i)=jb(2,i)+mask(2,i)
            jb(7,i)=jb(2,i)+mask(3,i)
            jb(8,i)=jb(2,i)+mask(4,i)
            jb(9,i)=jb(3,i)+mask(3,i)
            jb(10,i)=jb(3,i)+mask(4,i)
            jb(11,i)=jb(4,i)+mask(4,i)
            jb(12,i)=jb(6,i)+mask(3,i)
            jb(13,i)=jb(6,i)+mask(4,i)
            jb(14,i)=jb(7,i)+mask(4,i)
            jb(15,i)=jb(9,i)+mask(4,i)
            jb(16,i)=jb(12,i)+mask(4,i)
36      continue

        do 56 j=1,16
           do 37 i=1,24
              jb(j,i)=and(jb(j,i),1)
37         continue
56      continue

        return
        end

c-------------------------------------------------------------------------------

c       exclusive or of two integer*4s
c       one bit per integer*4

        subroutine exor(i,j,k)

        integer*4 i,j,k

        i=and(j+k,1)

        return
        end

c-------------------------------------------------------------------------------

c       binary table look-up decoder for golay (24,12) code
```

```
      subroutine golay

      integer*4 idata(24),ierr(5),kdata(24),is(11)
      integer*4 isym(2047)
      real conf(24)
      common/blk5/idata
      common/blk7/conf,isym,kdata,ierr

      n=23
      ierr(5)=0

c     generate syndrome
c      write(6,*) 'generating golay syndrome'
      call encode(kdata,is,n)

c     use syndrome to generate index to table
      ir=0
      do 38 j=1,11
         ir=ir*2+is(j)
38    continue

      if(ir.ne.0)then
c        look up error pattern
c        possibility of up to 3 errors
c        recorded as three 5-bit symbols in a 16-bit word
         ix=isym(ir)
c        identify error locations and count errors
         do 39 j=1,3
            ierr(j)=and(ix,31)
            if(ierr(j).gt.0)ierr(5)=ierr(5)+1
            ix=ix/32
c     if(ierr(j).gt.0)write(6,*)'ierr(j)=',ierr(j)
39       continue
end if

c     test overall parity
      ir=ierr(5)
      do 41 j=1,24
         ir=ir+kdata(j)
41    continue

      ir=and(ir,1)

c     test for even parity
      if (ir.ne.0) then
```

```
c          parity check failed
c          force overall parity
c          increment error count
           ir=ierr(5)+1
           ierr(ir)=24
           ierr(5)=ir
end if

        return
        end

c-------------------------------------------------------------------------------

c       golay(23,12) encoder, syndrome generator

        subroutine encode(idata,ip,n)

        integer*4 idata(12),ip(11),ix

c       g(x)=x**11+x**9+x**7+x**6+x**5+x+1
c       clear ip
        do 42 i=1,11
           ip(i)=0
42      continue

c       read in n bits
        do 43 i=1,n
           call exor(ix,idata(i),ip(1))
           ip(1)=ip(2)
           call exor(ip(2),ix,ip(3))
           ip(3)=ip(4)
           call exor(ip(4),ix,ip(5))
           call exor(ip(5),ix,ip(6))
           call exor(ip(6),ix,ip(7))
           ip(7)=ip(8)
           ip(8)=ip(9)
           ip(9)=ip(10)
           call exor(ip(10),ix,ip(11))
           ip(11)=ix
43      continue

        return
        end

c-------------------------------------------------------------------------------
```

```
        subroutine bitgen11(nbits,ival,data)

c this routine generates a pseudorandom sequence of bits using an 11 bit
c shift register, exoring the 9th and 11th bits to generate the new 1st bit
c before shifting.  the length of the pseudorandom sequence is (2**11)-1
c or 2047 bits.

        integer*4 data, shindex, nbits, ival, index, temp
        integer*4 lshift, rshift, xor

        if (ival .gt. 0 .and. ival .lt. 2048) index = ival

        data = 0
c ensure that all bits in data are 0

        call mvbits(index,0,nbits,data,0)
c move bits from index to data

        shindex = lshift(index,2)
c shindex is index shifted left 2

        temp = xor(index,shindex)
c temp contains new bits for index

        index = rshift(index,nbits)
c shift index right by nbits

        call mvbits(temp,2,nbits,index,11-nbits)
c move new bits, temp to index

        return
        end

c-------------------------------------------------------------------------

c  golay encoder

subroutine golenc

integer*4 idata(24),id(12),is(11)
common/blk5/idata

n=12
```

```
c load 12 information bits
c sum inf bits for overall parity
do 44 j=1,12
        id(j)=idata(j)
44      continue

c encode using n-k type shift register
call encod(id,is,n)

c store parity bits in same array as inf bits
do 45 j=1,11
        idata(j+12)=is(j)
45      continue

c generate over all parity bit(even parity)
c store as 24th bit in array
        m=0

        do 46 j=1,23
            m=m+idata(j)
46      continue

idata(24)=and(m,1)

return
end

c-------------------------------------------------------------------------

c golay(23,12) encoder, syndrome generator
c x11+x9+x7+x6+x5+x+1

subroutine encod(idata,ip,n)
integer*4 idata(12),ip(11),ix

c clear ip
do 47 i=1,11
       ip(i)=0
47      continue

c read in n bits
  do 48 i=1,n
   call exor(ix,idata(i),ip(1))
   ip(1)=ip(2)
   call exor(ip(2),ix,ip(3))
```

```
   ip(3)=ip(4)
   call exor(ip(4),ix,ip(5))
   call exor(ip(5),ix,ip(6))
   call exor(ip(6),ix,ip(7))
   ip(7)=ip(8)
   ip(8)=ip(9)
   ip(9)=ip(10)
   call exor(ip(10),ix,ip(11))
          ip(11)=ix
48    continue

return
end

c--------------------------------------------------------------------------

        subroutine bitgen11fill(nbits,ival,data)

c this routine generates a pseudorandom sequence of bits using an 11 bit
c shift register, exoring the 9th and 11th bits to generate the new 1st bit
c before shifting.  the length of the pseudorandom sequence is (2**11)-1
c or 2047 bits.

        integer*4 data, shindex, nbits, ival, index, temp
        integer*4 lshift, rshift, xor

        if (ival .gt. 0 .and. ival .lt. 2048) index = ival

        data = 0
c ensure that all bits in data are 0

        call mvbits(index,0,nbits,data,0)
c move bits from index to data

        shindex = lshift(index,2)
c shindex is index shifted left 2

        temp = xor(index,shindex)
c temp contains new bits for index

        index = rshift(index,nbits)
c shift index right by nbits

        call mvbits(temp,2,nbits,index,11-nbits)
c move new bits, temp to index
```

```
        return
        end

c -------------------------------------------------------------------------

        subroutine tx(dibit,txsamp)

        dimension txbuff(32), txsamp(3)
        integer*4 dibit, index, i
        real txbuff, txsamp
        data txbuff, index  / 32*0., 1 /

        call modulate(dibit,index,txbuff)
c modulate one baud or symbol

c add symbol to transmit buffer
c note : each symbol is filtered by the modulator to be wider than
c one baud so as to restrict the bandwidth to about 4000 Hz for
c reduction of ACI (adjacent channel interference), so that the resulting
c baud pulses overlap and must be added together

        do 49 i = 1, 3
           txsamp(i) = txbuff(index)
           txbuff(index) = 0
           index = mod(index,32) + 1
49      continue

        return
        end

c -------------------------------------------------------------------------

        subroutine modulate(mbit,index,buffer)

        integer*4 mbit, phasec, cphase, tphase
        integer*4 point, wlength, i, index, modangle
        real s, pi, buffer, w
        dimension phasec(4), w(29), buffer(*)

        data phasec / 225,135,315,45 /
        data wlength, modangle, cphase, pi / 29, 0, 0, 3.141593 /

c this is the transmit window to shape the output spectrum to about
c 4000 Hz wide
```

```
      data w / -.005696,.062601,.028191,-.021020,-.060997,
     *  -.035666,.049659,.106424,.043728,-.114226,-.203894,
     *  -.049151,.358925,.805832,.999756,.805832,.358925,
     *  -.049151,-.203894,-.114226,.043728,.106424,.049659,
     *  -.035666,-.060997,-.021020,.028191,.062601,-.005696/

      modangle = phasec(mbit + 1)
c modulation phase change angle

      cphase = mod(cphase + 270, 360)
c continuous unmodulated carrier phase

      tphase = mod(cphase + modangle, 360)
c actual transmit phase

      point = index

c take the sine wave of the actual transmit phase and window it
      do 51 i = 1, wlength
         s = .364 * w(i) * sin(pi / 180. * (tphase + 90 * i))
         buffer(point) = buffer(point) + s
         point = mod(point, 32) + 1
51    continue

      return
      end

c -------------------------------------------------------------------------

      subroutine rcv(samples,dbits,xdisp,ydisp,confh,confl)

c  purpose: this routine demodulates an 8000 b/s 4 phase dpsk modem signal.
c           it is called once to demodulate each baud.

c  inputs:  sigin - contains samples of the signal to be demodulated.
c                   sigin(1) is first in time.

c  outputs: dbits - an integer which contains the 2 demodulated bits.
c                   The data is stored in the least significant bits;
c                   the lsb is first in time.

c  brief description of subroutine functions:

c  equalize -    calculates the output of the adaptive equalizer.
c  decode -      uses the equalizer output to determine the data bits.
```

```
c                a phase reference is calculated for internal use.

        integer*4 dbits, i
real confh,confl
        real signal, x, y
        real xdisp,ydisp
        real signal(48), samples(3)
real xcoef(48),ycoef(48)

        common /adequ/ xcoef, ycoef

c compromise equalizer coefficients for removing the intersymbol
c interference introduced by the transmitter  windowing :
data xcoef / 0.00047277, 0.00018969, 0.00152612,-0.00026510,
     1  0.00288611,-0.00077746, 0.00057433,-0.00176436,
     1 -0.00299245,-0.00031443,-0.01333420, 0.00245006,
     1  0.00073868, 0.00575836, 0.00552585, 0.00128170,
     1  0.01571514,-0.00732426, 0.00609350,-0.01291209,
     1 -0.03999998,-0.00832545,-0.10446436, 0.00526107,
     1 -0.14213182, 0.01429809, 0.38911167, 0.03028025,
     1 -0.06119568, 0.01810114,-0.00429513, 0.00713205,
     1  0.01294118, 0.00074462, 0.00006572, 0.00038059,
     1 -0.01742128, 0.00060559,-0.00858223, 0.00059077,
     1  0.00697080,-0.00119318, 0.00344639,-0.00073849,
     1  0.00324149,-0.00039312, 0.00125349,-0.00045128/
data ycoef / -0.00016221, 0.00070496,-0.00036193,-0.00072445,
     1 -0.00059857,-0.00178603,-0.00014448,-0.00418214,
     1  0.00070030, 0.00100549, 0.00305764, 0.00433583,
     1  0.00079199, 0.00792035,-0.00374299, 0.01238339,
     1 -0.00632491,-0.01299071, 0.00042162,-0.03951978,
     1  0.01424530,-0.02844719, 0.02507262, 0.05758527,
     1  0.02317356, 0.35042825, 0.01940719,-0.24283291,
     1  -0.00569436,-0.01806669,-0.01134070,-0.00663402,
     1 -0.00711616,-0.02175912,-0.00075678,-0.01645218,
     1  0.00256463,-0.00212019, 0.00016785, 0.02115092,
     1 -0.00076241, 0.00839603,-0.00143184,-0.00148724,
     1 -0.00056496,-0.00391606,-0.00031074,-0.00173826/

        data signal / 48*0.0 /

c  signal buffer is as long as the equalizer that it will multiply against
c or 48 samples long

        do 52 i = 1, 45
c          shift signal buffer to accomodate new samples
```

```
            signal(i) = signal(i+3)
52        continue

          do 53 i = 46, 48
c            put new samples into signal buffer
             signal(i) = samples(i-45)
53        continue

          call equalize(signal,x,y)

          call decode(x,y,dbits,xdisp,ydisp,confh,confl)

          return
          end

c-------------------------------------------------------------------------------

          subroutine equalize(signal,x,y)

c  purpose:  this routine generates the output of the equalizer; i.e., it
c            c culates the output value of each fir equalizer filter.

c  input:    signal - a real array which contains the received signal samples.
c            signal(1) is first in time.

c  outputs:  x - the x-coordinate of the equalizer output.
c            y - the y-coordinate of the equalizer output.

          integer*4 i
          real x, y
real xcoef(48),ycoef(48)
          real signal(48)

          common /adequ/ xcoef, ycoef

          y = 0.
          x = 0.

          do 54 i = 1,48
             x = x + signal(i) * xcoef(i)
             y = y + signal(i) * ycoef(i)
54        continue

x=2.*x
y=2.*y
```

```
        return
        end

c-------------------------------------------------------------------------

        subroutine decode(x,y,dibit,xdisp,ydisp,confh,confl)

c  purpose:  this routine determines the data bits given the x,y coordinates
c            from the equalizer.

c  inputs:   x - the x-coordinate of the demodulated baud.
c            y - the y-coordinate of the demodulated baud.

c  outputs:  dibit - the 2 data bits for the current baud; lsb is first in time.

        integer*4 dibit
        real mag, phaser, x, y, qang, preang, phasech, arctan
        real angle, decang, angdisp, xdisp, ydisp, error
        real angtab
        dimension  angtab(4)
real predecang,diffang
real confh,confl
real desmag

        data angtab / -.75, -.25, .25, .75 /
        data preang / 0. /

        angle = arctan(y,x)
c convert from rectangular to polar coordinates

        decang = angle - phaser
c decang is the angle to be decoded

        call adjust(decang)

c  calculate dibit:

c       preang=qang
c  previously quantized angle

c       qang = angtab(int(2.*decang+2.)+1)
c  quantized angle

c       phasech = qang - preang
```

```
c  quantized phase change

c       if(phasech.lt.0.0)phasech=phasech+2.
c       if(phasech.eq.0.0)dibit=2
c  phase change of 0
c       if(phasech.eq.0.5)dibit=0
c  phase change of 90
c       if(phasech.eq.1.0)dibit=1
c  phase change of 180,or -180
c       if(phasech.eq.1.5)dibit=3
c  phase change of -90

diffang=decang-predecang
c  unquantized phase change

call adjust(diffang)

        predecang=decang
c  previous decoded angle update

c compute confidence values :
if(diffang.lt.-.75)then
           dibit=1
   confl=(diffang+1.25)*2.
   confh=-(diffang+.75)*2.
else if(diffang.lt.-.25)then
           dibit=3
   confl=-(diffang+.25)*2.
   confh=(diffang+.75)*2.
else if(diffang.lt.0.25)then
           dibit=2
   confl=(diffang+.25)*2.
   confh=-(diffang-.25)*2
else if(diffang.lt.0.75)then
           dibit=0
   confl=-(diffang-.75)*2.
   confh=(diffang-.25)*2.
else
           dibit=1
   confl=(diffang-.75)*2.
   confh=-(diffang-1.25)*2.
end if

c       calculate x and y values for constellation display:
```

```
        mag = sqrt(x*x + y*y)
        angdisp = (diffang+.25)
        call adjust(angdisp)
        angdisp = angdisp * 3.141593

        xdisp = mag * cos(angdisp)
        ydisp = mag * sin(angdisp)

desmag=.707/2
c scale the confidence by the radius (lower confidence in fade) :
if(mag.lt.desmag)then
   confl=confl*mag/desmag
   confh=confh*mag/desmag
end if

c  calculate error angle :

c       error = decang - qang
c       call adjust(error)

c  update phase reference for next baud:

        phaser = phaser - .5
c                           the .5 comes from .25 (times 180 degrees)
c     of carrier advance per baud plus .25
c     (or 45 degrees) thus shifting the phase computations
c     from 135,45,-45,-135 to the 90,0,-90,-180 domain
        call adjust(phaser)

        return
        end

c-------------------------------------------------------------------------------

        function arctan(y,x)

c  4 quadrant arctangent  -1 <= arctan < 1
c  -1 corresponds to -180 degrees

        real arctan, y, x

        arctan = 0.0
        if (x .ne. 0.0 .or. y .ne. 0.0) arctan = atan2(y,x)/3.141593

        return
```

```
        end

c-------------------------------------------------------------------------

        subroutine adjust(value)

c  routine to ensure value is kept in range -1 to 1.

        real value

        value = amod(value,2.)
        if (value .lt. -1.) value = value + 2.
        if (value .ge. 1.)  value = value - 2.

        return
        end

c-------------------------------------------------------------------------

subroutine sim(samples,noise,noisef,mode,iseed,gaus,n,sf,mk)

c------------------variables and parameters----------------------
c noise=signal/noise in dB
c mode = 0 for non-fading, 1 for fading

real samples(3)
        real gaus(256)
c gaussian distribution of noise table
real noise,noisef
real sv(120),nv(120)
real sdb,ndb
integer*4 sinn,nin,n,sf
integer*4 fade,mode,fadecnt
integer*4 iseed
        integer*4 ms10,ms20,ms40,ms100,ms200

c------------------------variable initialization--------------------------

if (ifirst.eq.0) then
   rgn = (10.**(-noise/20.))
c  compute actual noise scaler from dB

           rgnf = (10.**(-noisef/20.))
c  compute noisef scaler from dB
   ifirst=1
```

```
   test=rand(iseed)
           fade = 0
           fadecnt = 0
           ms10 = 0
           ms20 = 0
           ms40 = 0
           ms100 = 0
           ms200 = 0
end if

c-----------------------------------------------------------------------

do 55 m=1,3

c measure the RMS of past 120 samples of signal
   s = samples(m)
   sinn = mod(sinn+1,120)
   sdb = (sdb**2.)-sv(mod(sinn+1,120)+1)
   sv(sinn+1) = (s**2.)/120.
   sdb = sdb + sv(sinn+1)
   if (sdb.lt.0.) sdb = 0.
   sdb = sqrt(sdb)

c measure the RMS of past 120 samples of noise (direct from table)
   nin = mod(nin+1,120)
   ndb = (ndb**2.)-nv(mod(nin+1,120)+1)
   k = (255.*rand(0)) + 1
   nv(nin+1) = ((gaus(k)/25295.)**2.)/120.
   ndb = ndb + nv(nin+1)
   if (ndb.lt.0.) ndb = 0.
   ndb = sqrt(ndb)

   if(mode.eq.1)then
      if(fadecnt.eq.0)then
         if(rand(0).gt..94056)then
            fade=1
            test=rand(0)
            if(test.lt.0.8)then
                  fadecnt=120
                        ms10 = ms10 + 1
            else if(test.lt.0.9)then
                  fadecnt=240
                        ms20 = ms20 + 1
            else if(test.lt.0.95)then
                  fadecnt=480
```

```
                        ms40 = ms40 + 1
            else if(test.lt.0.99)then
               fadecnt=1200
                        ms100 = ms100 + 1
            else
               fadecnt=2400
                        ms200 = ms200 + 1
            end if
         else
            fade=0
            fadecnt=120
         end if
       else
          fadecnt=fadecnt-1
       end if

              if((n.eq.sf).and.(mk.eq.1680).and.(m.eq.3))then
                 write(6,*)' number of 10ms fades in ',sf,
     *' runs = ',ms10
                 write(6,*)' number of 20ms fades in ',sf,
     *' runs = ',ms20
                 write(6,*)' number of 40ms fades in ',sf,
     *' runs = ',ms40
                 write(6,*)' number of 100ms fades in ',sf,
     *' runs = ',ms100
                 write(6,*)' number of 200ms fades in ',sf,
     *' runs = ',ms200
              end if
           end if

      if((mode.eq.0).or.((mode.eq.1).and.(fade.eq.0)))then
c     not in fade
         if (rand(0).ge.0.5) then
            if (ndb.ne.0.) samples(m) = samples(m) +
     1             (gaus(k)/25295.)*(sdb/ndb)*(rgn)
          else
            if (ndb.ne.0.) samples(m) = samples(m) -
     1             (gaus(k)/25295.)*(sdb/ndb)*(rgn)
          end if
      end if

      if((mode.eq.1).and.(fade.eq.1))then
c     we are in fade
         if (rand(0).ge.0.5) then
c     make positive noise
```

```
         if (ndb.ne.0.) samples(m) = samples(m) +
     1             (gaus(k)/25295.)*(sdb/ndb)*(rgnf)
       else
c  make negative noise
         if (ndb.ne.0.) samples(m) = samples(m) -
     1             (gaus(k)/25295.)*(sdb/ndb)*(rgnf)
       end if
   end if

c scale signal down in fade :
   if((mode.eq.1).and.(fade.eq.1))samples(m)=samples(m)/10.

55      continue

return
end

c*******************************************************************************

subroutine chsim(samples,noise,noisef,mode,iseed,gaus,bprob,bwidth)

c------------------variables and parameters----------------------
c noise=signal/noise in dB
c mode = 0 for non-fading, 1 for fading

real samples(3)
        real gaus(256)
c***** gaussian distribution of noise table
real noise,noisef,bprob
real sv(120),nv(120)
real sdb,ndb,rtest
integer*4 sinn,nin
integer*4 fade,mode,fadecnt
integer*4 iseed,bwidth

c-------------------------variable initialization--------------------------

if (ifirst.eq.0) then
   rgn = (10.**(-noise/20.))
c***** compute actual noise scaler from dB

           rgnf = (10.**(-noisef/20.))
c***** compute noisef scaler from dB
   ifirst=1
   test=rand(iseed)
```

```
            fade = 0
            fadecnt = 0
            rtest = 1. - (1.-bprob)/120
end if

c-----------------------------------------------------------------

do 55 m=1,3

c***** measure the RMS of past 120 samples of signal
   s = samples(m)
   sinn = mod(sinn+1,120)
   sdb = (sdb**2.)-sv(mod(sinn+1,120)+1)
   sv(sinn+1) = (s**2.)/120.
   sdb = sdb + sv(sinn+1)
   if (sdb.lt.0.) sdb = 0.
   sdb = sqrt(sdb)

c***** measure the RMS of past 120 samples of noise (direct from table)
   nin = mod(nin+1,120)
   ndb = (ndb**2.)-nv(mod(nin+1,120)+1)
   k = (255.*rand(0)) + 1
   nv(nin+1) = ((gaus(k)/25295.)**2.)/120.
   ndb = ndb + nv(nin+1)
   if (ndb.lt.0.) ndb = 0.
   ndb = sqrt(ndb)

   if(mode.eq.1)then
      if(fadecnt.eq.0)then
         if(rand(0).gt.rtest)then
            fade=1
                    fadecnt = bwidth
         else
            fade=0
            fadecnt=0
         end if
      else
         fadecnt=fadecnt-1
      end if
   end if

c***** not in fade
   if((mode.eq.0).or.((mode.eq.1).and.(fade.eq.0)))then
      if (rand(0).ge.0.5) then
         if (ndb.ne.0.) samples(m) = samples(m) +
```

```
     1             (gaus(k)/25295.)*(sdb/ndb)*(rgn)
      else
         if (ndb.ne.0.) samples(m) = samples(m) -
     1             (gaus(k)/25295.)*(sdb/ndb)*(rgn)
      end if
   end if

c***** we are in fade
   if((mode.eq.1).and.(fade.eq.1))then
c***** make positive noise
      if (rand(0).ge.0.5) then
         if (ndb.ne.0.) samples(m) = samples(m) +
     1             (gaus(k)/25295.)*(sdb/ndb)*(rgnf)
c***** make negative noise
      else
         if (ndb.ne.0.) samples(m) = samples(m) -
     1             (gaus(k)/25295.)*(sdb/ndb)*(rgnf)
      end if
   end if

c***** scale signal down in fade :
   if((mode.eq.1).and.(fade.eq.1))samples(m)=samples(m)/200.

55      continue

return
end

c*****************************************************************

c               encodeham
c
c FUNCTION
c               This subroutine calculates the parity bits necessary
c to form the codeword.
c
c
c SYNOPSIS
c               encodeham(codelength1,codelength2,hmatrix,
c   paritybit,codeword)
c
c   formal
c
c                       data    I/O
c       name            type    type    function
```

```
c       ------------------------------------------------------------------
c       codelength1 int i number of data bits (63)
c codelength2 int i number of information bits (57)
c hmatrix int i vector to encode an decode by
c paritybit int o overall parity bit
c codeword int o encoded stream (paritybits at end)
c
c=================================================================================
c
c DESCRIPTION
c
c This subroutine is part of a set of subroutines which perform
c a Generalized Hamming Code.  As you know, Hamming codes are perfect
c codes and can only detect and correct one error.  We added an overall
c  parity checkbit, which allows us to detect 2 errors.  When 2 errors
c are detected, (in subroutine decodeham.f) no correction attempt is
c made.  This would most likely result in more errors.  Instead, a flag
c is sent to the calling program notifying it of multiple errors so
c that smoothing may be attempted.  The Hamming codes presently supported
c by the routines are (63,57), (31,26), (15,11), and shortened variations
c thereof.  It could be made even more general by making minor modifications
C to the dectobin.f subroutine.  This routine at present will calculate
c a maximum of 6 bits.
c
c Hamming routines consist of the following files:
c
c matrixgen - generates the hmatrix and sydrometable.
c dectobin - does a simple decimal to binary conversion.
c encodeham - generates the codeword and overall paritybit.
c decodeham - recovers infobits, checks for errors, corrects 1
c error, and sends out flag for smoothing.
c
c
c               This subroutine performs the Hamming encode function.
c It will calculate the necessary parity bits, depending on which code
c is requested, and will add the overall parity bit to the end of the
c codeword generated.
c
c
c=================================================================================
c
c REFERENCES
c
c Lin and Costello : Error Control Coding
c Berlekamp : Algebraic Coding Theory
```

```
c
c*************************************************************************
c
subroutine encodeham(codelength1,codelength2,hmatrix,
     1     paritybit,codeword)
c
integer*4 codelength1,codelength2,paritybit
integer*4 codeword(codelength1),hmatrix(codelength1)
integer*4 parityflag,temp1,temp2,i,temp3
c
paritybit=0
parityflag=0
c *** parityflag = 0 if not using the extra parity bit.
temp1=codelength1-codelength2
temp2=0
temp3=0
c
c First generate the parity bits for the Hamming codeword.  This is
c relatively straightforward.  hmatrix was generated in matrixgen.f,
c which is called as part of the Hamming initialization routines.
c
do 10 i=1, codelength2
   if(codeword(i).ne.0) temp2= xor(temp2,hmatrix(i))
10 continue
c
c since the hmatrix is stored in a packed decimal format, the parity
c bits must be unpacked and appended to the end of the bitsteam.
c after this routine you will have the complete codeword.
c
call dectobin(temp1,temp2,codeword(codelength2+1))
c
c Now I check to see if the parityflag is set, indicating the user
c requests an overall parity bit be generated.  Normally this will
c be the case.
c
temp2=0
if (parityflag.eq.1)then
   do 20 i=1,codelength1
      temp2 = xor(temp2,codeword(i))
      if (codeword(i).ne.0) temp3=temp3+1
20    continue
   paritybit=temp2
end if
c
return
```

```
end

c=======================================================================
c
c ROUTINE
c               decodeham
c
c FUNCTION
c               This subroutine decodes the bitstream generated by
c encodeham.  It will correct a single error, and detect 2
c errors.
c
c
c SYNOPSIS
c               subroutine decodeham(codelength1,codelength2,hmatrix,
c syndrometable,paritybit,codeword,myerror)
c
c   formal
c
c                       data    I/O
c       name            type    type    function
c       ------------------------------------------------------------
c       codelength1 int i number of data bits
c codelength2 int i number of information bits
c hmatrix int i vector to encode an decode by
c syndrometable int i errormasks used to correct single
c errors
c paritybit int i overall parity bit
c codeword int i/o encoded/decoded stream
c myerror log o flag for 2 error detect
c synflag int o value 0 or 1, 1 if syndrome .ne. 0
c
c
c=======================================================================
c
c DESCRIPTION
c
c This subroutine is part of a set of subroutines which perform
c a Generalized Hamming Code.  As you know, Hamming codes are perfect
c codes and can only detect and correct one error.  We added an overall
c  parity checkbit, which allows us to detect 2 errors.  When 2 errors
c are detected, (in subroutine decodeham.f) no correction attempt is
c made.  This would most likely result in more errors.  Instead, a flag
c is sent to the calling program notifying it of multiple errors so
c that smoothing may be attempted.  The Hamming codes presently supported
```

```
c by the routines are (63,57), (31,26), (15,11), and shortened variations
c thereof.  It could be made even more general by making minor modifications
c to the dectobin.f subroutine.  This routine at present will calculate
c a maximum of 6 bits.
c
c Hamming routines consist of the following files:
c
c matrixgen - generates the hmatrix and sydrometable.
c dectobin - does a simple decimal to binary conversion.
c encodeham - generates the codeword and overall paritybit.
c decodeham - recovers infobits, checks for errors, corrects 1
c error, and sends out flag for smoothing.
c
c
c This subroutine, decodeham, is responsible for checking for errors,
c correcting the error if there is only one, and sending a smoothing flag
c to the calling routine if there is more than one.
c
c=======================================================================
c
c REFERENCES
c
c Lin and Costello : Error Control Coding
c Berlekamp : Algebraic Coding Theory
c
c***********************************************************************
c
        subroutine decodeham(codelength1,codelength2,paritybit,myerror,
     1   hmatrix,syndrometable,codeword)

integer*4 codelength1,codelength2,hmatrix(codelength1)
integer*4 syndrometable(codelength1),paritybit
        integer*4 codeword(codelength1),myerror
integer*4 errorflag,parityflag
integer*4 synflag, i, j, temp3

myerror=0
errorflag=0
parityflag=0
c *** parity flag = 0 if not using the extra parity bit
c
c     This part of the routine checks the overall parity of the codeword
c and compares it with the overall paritybit sent.  If they are not the
c same that means there is at least one error.  If, later on in the routine,
c the syndrome check indicates that there is an error and the parity is
```

```
c correct in this part of the routine, that indicates there are two errors.
c One of the weaknesses of this method is that there is no way of knowing
c if we have 3,5,7,... errors.  We always smooth if there are 2,4,6,...
c errors.
c
if (parityflag.eq.1) then
          synflag=0
   do 10 i=1,codelength1
      synflag= xor(synflag,codeword(i))
10    continue
   if (paritybit.ne.synflag)errorflag=errorflag+1
end if
c
c This part of the routine generates the syndrome.  The syndrome will
c equal zero if there are no errors.  synflag accumulates the syndrome
c and is used as the offset in the syndrome table, which tells the
c routine which bit is in error.
C
        synflag=0
temp3=0
do 30 i=1,codelength1
   if(codeword(i).ne.0)synflag = xor(synflag,hmatrix(i))
   if(codeword(i).ne.0)temp3 = temp3 + 1
30 continue
c
c *** Check to see if the parityflag is set and if it is then check
c to see if the parity bit was in error.
c If the parityflag was set and there was an error in the syndrome,
c the errorflag should equal 1.
c If it doesn't, then there are more errors than can be corrected
c and the infobits are passed on unchanged.
c
if (synflag.ne.0)then
   if((errorflag.ne.1) .and. (parityflag.eq.1))then
      myerror = 1
      go to 20
   end if
          j=syndrometable(synflag)
          codeword(j)=xor(codeword(j),1)
end if
c
c *** If the syndrome is equal to zero and the errorflag is set
c (not likely, but must be checked) then more than one error has
c occured, but it cannot be corrected, so I pass on the infobits
c the same as if there were no errors.
```

```
c
20      continue
return
end
c=======================================================================
c
c ROUTINE
c dectobin
c
c FUNCTION
c This subroutine converts decimal numbers into a
c binary output vector.
c
c SYNOPSIS
c dectobin(vectorsize, decinteger, binaryvector)
c
c   formal
c
c                       data    I/O
c       name            type    type    function
c       ------------------------------------------------------------------
c vectorsize int i output vector length
c decinteger int i decimal number  (< 2^32-1)
c binaryvector int o vector containing binary number
c
c=======================================================================
c
c DESCRIPTION
c
c This subroutine is part of a set of subroutines which perform
c a Generalized Hamming Code.  As you know, Hamming codes are perfect
c codes and can only detect and correct one error.  We added an overall
c  parity checkbit, which allows us to detect 2 errors.  When 2 errors
c are detected, (in subroutine decodeham.f) no correction attempt is
c made.  This would most likely result in more errors.  Instead, a flag
c is sent to the calling program notifying it of multiple errors so
c that smoothing may be attempted.  The Hamming codes presently supported
c by the routines are (63,57), (31,26), (15,11), and shortened variations
c thereof.  It could be made even more general by making minor modifications
c to the dectobin.f subroutine.  This routine at present will calculate
c a maximum of 6 bits.
c
c Hamming routines consist of the following files:
c
c matrixgen - generates the hmatrix and sydrometable.
```

```
c dectobin - does a simple decimal to binary conversion.
c encodeham - generates the codeword and overall paritybit.
c decodeham - recovers infobits, checks for errors, corrects 1
c error, and sends out flag for smoothing.
c
c
c This routine is used by encodeham to convert the packed decinteger
c into the Hamming paritybits.
c
c*************************************************************************
c
c REFERENCES
c
c Lin and Costello : Error Control Coding
c Berlekamp : Algebraic Coding Theory
c
c*************************************************************************
c
subroutine dectobin(vectorsize, decinteger, binaryvector)
c
integer*4 vectorsize, decinteger, binaryvector(vectorsize)
integer*4 i, temp1, twostable(6)
c
data twostable/1,2,4,8,16,32/
c
c Check to see if the decimal integer is larger than the routine can
c convert.  This can be easily extended by adding to the twostable.
c
if (decinteger .gt. 63)
     &     print *,'dectobin:  decinteger too large', decinteger
temp1=vectorsize
do 10 i=1,vectorsize
   if(decinteger.ge.twostable(temp1))then
      binaryvector(temp1)=1
      decinteger=decinteger-twostable(temp1)
   else
      binaryvector(temp1)=0
   end if
   temp1=temp1-1
10 continue
return
end
c=========================================================================
c
c ROUTINE
```

```
c matrixgen
c
c FUNCTION
c
c This routine is used to generate the H matrix and
c syndrome table necessary for Hamming encode and decode.  This
c routine should be called once before calling encodeham and
c decodeham.
c
c SYNOPSIS
c subroutine matrixgen(codelength1,codelength2,
c hmatrix,syndrometable)
c
c   formal
c
c                        data    I/O
c       name             type    type    function
c       ------------------------------------------------------------------
c codelength1 int i number of data bits (63)
c codelength2 int i number of information bits (57)
c hmatrix int o vector to encode an decode by
c syndrometable  int o table containing error masks
c
c=========================================================================
c
c DESCRIPTION
c
c This subroutine is part of a set of subroutines which perform
c a Generalized Hamming Code.  As you know, Hamming codes are perfect
c codes and can only detect and correct one error.  We added an overall
c  parity checkbit, which allows us to detect 2 errors.  When 2 errors
c are detected, (in subroutine decodeham.f) no correction attempt is
c made.  This would most likely result in more errors.  Instead, a flag
c is sent to the calling program notifying it of multiple errors so
c that smoothing may be attempted.  The Hamming codes presently supported
c by the routines are (63,57), (31,26), (15,11), and shortened variations
c thereof.  It could be made even more general by making minor modifications
c to the dectobin.f subroutine.  This routine at present will calculate
c a maximum of 6 bits.
c
c Hamming routines consist of the following files:
c
c matrixgen - generates the hmatrix and sydrometable.
c dectobin - does a simple decimal to binary conversion.
c encodeham - generates the codeword and overall paritybit.
```

```
c decodeham - recovers infobits, checks for errors, corrects 1
c error, and sends out flag for smoothing.
c
c This routine is initializes all of the tables necessary to perform
c the Hamming code (G Matrix, Syndrome Table) .
c
c=====================================================================
c
c REFERENCES
c
c Lin and Costello : Error Control Coding
c Berlekamp : Algebraic Coding Theory
c
c*********************************************************************
c
subroutine matrixgen(codelength1,codelength2,hmatrix,syndrometable)
c
integer*4 codelength1,codelength2
  integer*4 hmatrix(codelength1),syndrometable(codelength1)
integer*4 itemplate(6),ptemplate(57),i,temp1
c
c This is the data necessary to construct the G Matrix and the Syndrome
c Table.  If a larger code is desired, this table can be easily added to.
c All other routines, except the syndrome table construction,
c are general enough to calculate any size Hamming Code.
c
data itemplate/1,2,4,8,16,32/
data ptemplate/3,5,6,7,9,10,11,12,13,14,15,17,18,19,
     + 20,21,22,23,24,25,26,27,28,29,30,31,33,34,35,36,37,38,39,40,41,
     + 42,43,44,45,46,47,48,49,50,51,52,53,54,55,56,57,58,59,60,61,62,
     + 63/
c
c  Construct the parity portion of the hmatrix
c
do 30 i=1,codelength2
   hmatrix(i)=ptemplate(i)
30 continue
c
c Construct the identity portion of the hmatrix.
c
do 20 i=1,(codelength1-codelength2)
   hmatrix((codelength2+i))=itemplate(i)
20 continue
c
c Construct the syndrometable.  This routine is rather simple because
```

```
c I chose to arrange my G matrix sequentially (Berlrkamp method).
c I placed the parity bits in front in ascending order then added the
c bits left over in ascending order.  Since our code is linear I can get
c away with this.  If a larger Hamming code is needed, then a new
c exception must be generated for each parity bit.
c
temp1=1
do 10 i=1,codelength1
   if(i.eq.1)then
      syndrometable(i)=codelength2+1
      goto 10
   end if
   if(i.eq.2)then
      syndrometable(i)=codelength2+2
      goto 10
   end if
   if(i.eq.4)then
      syndrometable(i)=codelength2+3
      goto 10
   end if
   if(i.eq.8)then
      syndrometable(i)=codelength2+4
      goto 10
   end if
   if(i.eq.16)then
      syndrometable(i)=codelength2+5
      goto 10
   end if
   if(i.eq.32)then
      syndrometable(i)=codelength2+6
      goto 10
   end if
   syndrometable(i)=temp1
   temp1=temp1+1
c
10 continue
c
return
end
```

C. DATA INPUT

```
******************** Gaussian Input *****************

   20.    60.   100.   140.   181.   221.   261.   301.
  341.   381.   421.   462.   502.   542.   582.   622.
  662.   702.   743.   783.   824.   864.   904.   944.
  985.  1025.  1065.  1106.  1146.  1187.  1227.  1268.
 1309.  1350.  1390.  1431.  1472.  1513.  1553.  1594.
 1635.  1676.  1717.  1758.  1798.  1840.  1881.  1922.
 1963.  2005.  2046.  2088.  2129.  2170.  2212.  2254.
 2296.  2337.  2379.  2421.  2463.  2505.  2546.  2589.
 2631.  2673.  2716.  2758.  2800.  2843.  2886.  2928.
 2972.  3014.  3057.  3100.  3144.  3186.  3230.  3273.
 3316.  3360.  3404.  3448.  3492.  3535.  3579.  3624.
 3668.  3712.  3757.  3801.  3846.  3891.  3936.  3981.
 4026.  4072.  4117.  4163.  4209.  4254.  4300.  4346.
 4392.  4439.  4485.  4532.  4579.  4626.  4673.  4720.
 4767.  4815.  4863.  4911.  4959.  5007.  5056.  5104.
 5153.  5201.  5251.  5301.  5350.  5400.  5450.  5500.
 5550.  5600.  5651.  5702.  5754.  5805.  5857.  5908.
 5961.  6013.  6066.  6118.  6171.  6225.  6279.  6333.
 6387.  6442.  6496.  6551.  6606.  6662.  6719.  6774.
 6831.  6888.  6945.  7003.  7061.  7119.  7178.  7237.
 7296.  7356.  7417.  7477.  7538.  7599.  7661.  7724.
 7787.  7850.  7914.  7978.  8042.  8108.  8173.  8240.
 8306.  8373.  8441.  8510.  8579.  8649.  8719.  8790.
 8862.  8935.  9007.  9081.  9156.  9231.  9306.  9383.
 9461.  9540.  9619.  9700.  9781.  9863.  9947. 10031.
10117. 10203. 10290. 10380. 10470. 10561. 10654. 10748.
10843. 10941. 11039. 11140. 11241. 11345. 11451. 11558.
11668. 11780. 11893. 12010. 12129. 12250. 12374. 12500.
12631. 12764. 12901. 13041. 13186. 13334. 13488. 13646.
13809. 13978. 14153. 14335. 14524. 14721. 14928. 15143.
15371. 15610. 15864. 16134. 16423. 16734. 17071. 17439.
17847. 18305. 18827. 19440. 20186. 21150. 22545. 25295.
```

********** Golay Decoder Input **********

11	10	362	9	361	329	11593	8	360	328
11592	296	11560	10536	22946	7	359	327	11591	295
11559	10535	16869	263	11527	10503	18563	9479	24198	21889
20014	6	358	326	11590	294	11558	10534	20033	262
11526	10502	17932	9478	24199	15812	21667	230	11494	10470
21965	9446	24200	17506	22916	8422	24201	23141	15425	24203
756	18957	24202	5	357	325	11589	293	11557	10533
16871	261	11525	10501	20929	9477	19844	24145	21699	229
11493	10469	16873	9445	16874	16875	527	8421	22050	23142
23980	14755	23105	20610	16872	197	11461	10437	23682	9413
23086	20908	21763	8389	18925	23143	21795	16449	21827	21859
675	7365	12385	23144	21073	22084	19874	24001	16870	23146
16836	723	23147	17900	24197	23145	21731	4	356	324
11588	292	11556	10532	22161	260	11524	10500	18659	9476
19845	15814	24065	228	11492	10468	18691	9444	14401	24173
22918	8420	18755	18787	579	23088	21997	20642	18723	196
11460	10436	23714	9412	16803	15816	22919	8388	23201	15817
21101	15818	18978	494	15819	7364	20015	20993	22921	22085
22922	22923	716	13698	16837	24241	18627	19553	24196	15815
22920	164	11428	10404	23746	9380	19848	22625	18893	8356
19849	22029	23087	19851	620	20706	19850	7332	23181	17868
22113	22086	24099	20738	16868	24033	16838	20770	18595	20802
19847	642	20834	6308	23874	23906	738	22087	20961	20016
23842	21027	16839	18817	23810	24269	19846	15813	21635	22089
16840	15779	23778	690	22091	22090	22917	16843	526	23140
16842	22088	16841	20674	17825	3	355	323	11587	291
11555	10531	24012	259	11523	10499	18660	9475	17889	21104
21701	227	11491	10467	18692	9443	23219	17602	20897	8419
18756	18788	580	14757	16770	24271	18724	195	11459	10435
23183	9411	16804	17634	21765	8387	19906	23969	21797	23116
21829	21861	677	7363	12449	17698	24176	17730	18926	546
17762	22031	23085	20940	18628	19585	24195	17666	21733	163
11427	10403	20013	9379	21058	22657	21766	8355	24272	15746
21798	14759	21830	21862	678	7331	12481	24244	22978	14760
24100	20044	16867	14761	21103	17921	18596	461	14763	14762
21734	6307	12513	18958	21800	24175	21832	21864	680	21028
21833	21865	681	21866	682	683	21	12641	385	15780
12609	23184	12577	17570	21767	24130	12545	23139	21799	14758
21831	21863	679	131	11395	10371	18695	9347	16806	22689
19938	8323	18759	18791	583	24226	23182	17836	18727	7299
18760	18792	584	20972	24101	22030	18728	18794	586	587

18 19649 18761 18793 585 6275 16809 22124 17857 16811
525 24210 16810 21029 24044 23042 18662 19681 16808 15811
21668 24270 22146 15781 18694 19713 16807 17538 22915 19745
18758 18790 582 609 19809 19777 18726 5251 21998 22817
21004 22849 24103 705 22881 21030 13377 24174 18661 18959
19843 22785 21700 19970 24105 15782 18693 24107 753 22753
24106 23212 18757 18789 581 14756 24104 20578 18725 21032
23154 15783 23650 14722 16805 22721 21764 657 21035 21034
21796 21033 21828 21860 676 15786 12417 493 15787 22083
24102 15785 21102 21031 16835 15784 18629 19617 23010 24076
21732 2 354 322 11586 290 11554 10530 22952 258
11522 10498 22953 9474 22954 22955 717 226 11490 10466
21100 9442 14465 17603 24242 8418 22053 24078 15553 20047
16771 20644 22951 194 11458 10434 23716 9410 21996 17635
21006 8386 19907 22162 15585 16545 18980 24172 22950 7362
23120 17699 15617 17731 19877 547 17763 13700 15681 15713
481 23214 24194 17667 15649 162 11426 10402 23748 9378
21059 22126 17793 8354 22055 15747 20048 16577 24046 20708
22949 7330 22056 18849 22979 24268 19878 20740 16866 22059
689 20772 22058 20804 22057 644 20836 6306 23876 23908
740 16641 19879 23119 23844 16673 23180 17869 23812 513
16737 16705 21602 20974 19881 22028 23780 19883 621 17571
19882 24131 22054 23138 15521 16609 19880 20676 18892 130
11394 10370 23749 9346 14561 18956 19939 8322 21007 20001
21964 24227 18982 20709 22948 7298 14625 23215 17933 14689
449 20741 14657 13702 24275 20773 18530 20805 14593 645
20837 6274 23877 23909 741 23187 18984 21921 23845 13703
18985 23043 23813 18987 593 15810 18986 13704 22147 20046
23781 24079 14529 17539 22914 428 13707 13706 15489 13705
18983 20677 22128 5250 23878 23910 742 17901 23216 20743
23846 23118 13409 20775 23814 20807 19842 647 20839 19971
18924 20776 23782 20808 14497 648 20840 20809 22052 649
20841 650 20842 20 651 23914 746 747 23 14723
23881 23913 745 22127 23880 23912 744 16513 18981 20710
23848 23073 23879 23911 743 22082 19876 20742 23847 13701
16834 20774 23815 20806 23011 646 20838 98 11362 10338
22017 9314 21061 17638 19940 8290 19910 15749 24209 24228
16775 18881 22947 7266 24045 17702 22981 17734 16776 550
17766 23169 16777 22125 18562 16779 524 17670 16778 6242
19912 17703 18860 17735 24257 551 17767 19915 622 23044
19914 20973 19913 17671 21666 17737 22148 553 17769 554
17770 17 555 24133 19911 17704 15457 17736 16774 552
17768 5218 21065 15752 22983 21067 658 24077 21066 15754
13441 492 15755 23153 21064 15753 21698 19972 22986 22987
718 21985 21063 17605 22985 24134 22051 15751 22984 14754

16773 20611 24161 23213 17935 21089 23683 14724 21062 17637
21762 24135 19909 15750 21794 16481 21826 21858 674 24136
12353 17701 22982 17733 19875 549 17765 754 24139 24138
21005 24137 23012 17669 21730 4194 23084 20941 19945 24232
19946 19947 623 24233 13473 23046 18658 757 24235 24234
19944 19973 22150 23937 18690 23117 14433 17604 19943 17902
18754 18786 578 24231 16772 20643 18722 18913 22151 23048
23715 14725 16802 17636 19942 23050 19908 720 23051 24230
18979 23049 20865 22155 692 17700 22154 17732 22153 548
17764 13699 22152 23047 18626 19521 23013 17668 24013 19975
13569 22097 23747 14726 21060 22593 19941 13665 417 15748
13633 24229 13601 20707 17934 624 19979 19978 22980 19977
24098 20739 21932 19976 13537 20771 18594 20803 23014 643
20835 14729 23875 23907 739 460 14731 14730 23843 21026
13505 23045 23811 14728 23015 20045 21634 19974 22149 15778
23779 14727 23016 17572 18945 24132 23017 21953 20012 23019
719 20675 23018 1 353 321 11585 289 11553 10529
20038 257 11521 10497 20933 9473 17891 21895 24068 225
11489 10465 24273 9441 14466 21896 20899 8417 19981 21897
15554 21898 23109 684 21899 193 11457 10433 20041 9409
20042 20043 626 8385 23204 23971 15586 16546 14764 23185
20040 7361 12451 20996 15618 23021 22064 24005 20039 18990
15682 15714 482 19587 24193 21894 15650 161 11425 10401
20936 9377 24237 22659 17794 8353 20938 20939 654 16578
23111 19949 20937 7329 12483 18850 22116 21105 23112 24006
16865 24036 23113 17923 20935 23115 722 21893 23114 6305
12515 22063 23053 16642 20964 24007 20037 16674 24177 18820
20934 514 16738 16706 21601 12643 387 24009 12611 24010
12579 750 24011 22157 12547 23137 15522 16610 23110 24008
17828 129 11393 10369 15788 9345 14562 22691 24072 8321
23206 20002 24073 21069 24074 24075 752 7297 14626 20998
22117 14690 450 18991 14658 24037 21036 22989 18529 19651
14594 21892 24071 6273 23208 20999 17859 24108 20965 21922
20036 23211 725 18821 23210 19683 23209 15809 24070 21002
24141 656 21003 19715 14530 21001 22913 19747 23207 21000
15490 611 19811 19779 17829 5249 18992 22819 22119 22851
20966 707 22883 24039 13410 18822 20932 22062 19841 22787
24069 24040 22122 22123 691 16812 14498 22755 22121 751
24043 24042 22120 24041 23108 20545 17830 19917 20969 18824
23617 20971 655 22723 20970 18826 23205 588 18827 16514
20968 18825 17831 23074 12419 20997 22118 22081 20967 24004
17832 24038 16833 18823 17833 19619 17834 17835 557 97
11361 10337 22018 9313 17896 22692 20903 8289 17897 23974
23148 17899 559 18882 17898 7265 12485 19950 20905 24144
20906 20907 653 23170 24238 17925 18561 19652 17895 21891

20904 6241 12517 23976 17860 22158 24258 16876 20035 23978
21072 749 23979 19684 17894 23977 21665 12645 389 23218
12613 19716 12581 17473 20902 19748 12549 23975 15458 612
19812 19780 23054 5217 12518 22820 24143 22852 19982 708
22884 22130 13442 17927 20931 24204 17893 22788 21697 12646
390 17928 12614 21986 12582 22756 20901 17930 12550 560
17931 14753 23107 17929 24162 12647 391 21090 12615 18989
12583 22724 21761 23022 12551 23973 21793 16482 21825 21857
673 395 12 12650 394 12649 393 24003 12617 12648
392 17926 12616 19620 12584 21071 21729 4193 24211 22821
17862 22853 22092 709 22885 16844 13474 22159 18657 19686
17892 22789 24067 22061 23055 23938 18689 19718 14434 22757
20900 19750 18753 18785 577 614 19814 19782 18721 18914
17866 17867 558 19719 16801 22725 17865 19751 23203 23972
17864 615 19815 19783 20866 19752 12452 20995 17863 616
19816 19784 24239 617 19817 19785 18625 19 619 618
19818 22857 13570 713 22889 714 22890 22 715 13666
418 22824 13634 22856 13602 712 22888 21070 12484 22823
22115 22855 24097 711 22887 24035 13538 17924 18593 19653
22160 22791 15820 24240 12516 22822 17861 22854 20963 710
22886 21025 13506 18819 19983 19685 24142 22790 21633 12644
388 15777 12612 19717 12580 22758 18946 19749 12548 21954
24276 613 19813 19781 17827 65 11329 10305 22019 9281
14564 24207 17797 8257 24140 20004 15590 16581 22163 18883
22945 7233 14628 18853 15622 14692 452 23152 14660 23171
15686 15718 486 24109 14596 21890 15654 6209 21037 22988
15623 16645 24259 21924 20034 16677 15687 15719 487 517
16741 16709 15655 24243 15688 15720 488 21068 14532 17505
15656 15722 490 491 15 16613 15689 15721 489 5185
23151 18855 17801 16646 17802 17803 556 16678 13443 24277
20930 518 16742 16710 17800 18858 24208 589 18859 21987
14500 18857 17799 19916 22049 18856 15557 16614 23106 20609
24163 16680 22094 21091 23681 520 16744 16712 17798 521
16745 16713 15589 16 523 522 16746 23076 12386 18854
15621 16647 19873 24002 23220 16679 15685 15717 485 519
16743 16711 15653 4161 14631 20008 23186 14695 455 21926
14663 20010 13475 625 20011 23020 14599 20009 24066 14697
457 23939 14665 459 14 14698 458 22096 14632 20007
15556 14696 456 20641 14664 18915 19980 21929 23713 21930
14566 685 21931 24206 23202 20006 15588 16548 18977 21928
20867 23077 14630 20994 15620 14694 454 21927 14662 13697
15684 15716 484 19554 14598 24274 15652 22156 13571 16878
23745 24178 14565 22626 17796 13667 419 20005 13635 16580
13603 20705 22095 23078 14629 18852 22114 14693 453 20737
14661 24034 13539 20769 23052 20801 14597 641 20833 23079

```
23873 23905   737 16644 20962 21925 23841 16676 13507 18818
23809   516 16740 16708 23150   721 23083 23082 23777 23081
14533 19948 18947 23080 21106 21955 15524 16612 24236 20673
17826  3137 22026 22027   688 19884 24262 18888 22025 23175
13476 18889 22024 18890 17890   590 18891 23176 20049 23940
22023 21989 14467 17601 20898   724 23179 23178 15555 23177
16769 18887 24165 18916 24265 21093 22022 24267   758 17633
24266 22060 19905 23970 15587 16547 24264 18886 20868 16845
12450 17697 15619 17729 24263   545 17761 23174 15683 15715
  483 19586 22093 17665 15651 24110 13572 21094 22021 21991
21057 22658 17795 13668   420 15745 13636 16579 13604 18885
24167 21993 12482 18851 22977   687 21995 21994 24168 23173
13540 17922 24169 21992 24170 24171   755 21098 12514   659
21099 16643 24261 21097 15821 16675 13508 21096 23121   515
16739 16707 21569 12642   386 21095 12610 21990 12578 17569
18948 24129 12546 21956 15523 16611 21038 22956 24166 18918
13573 23943 22020 21040 14563 22690 19937 13669   421 20003
13637 24225 13605 18884 20870 23946 14627   748 23947 14691
  451 23945 14659 23172 13541 23944 18497 19650 14595 16877
23217   591 18923 18922 17858 18921 24260 21923 20872 18920
13509 23041 20873 19682 20874 20875   652 18919 22145 23942
23149 19714 14531 17537 18949 19746 24112 21957 15491   610
19810 19778 20871 13672   424 22818 13640 22850 13608   706
22882   427    13 13674   426 13673   425 22786 13641 19969
13575 23941 21039 21988 14499 22754 18950 13671   423 21958
13639 18988 13607 20577 24164 18917 13574 21092 23649 14721
22129 22722 18951 13670   422 21959 13638 16515 13606 24111
20869 23075 12418 21960 18953 24205 18954 18955   592 21962
13542   686 21963 19618 23009 21961 18952
```

APPENDIX B: Simulation Data

A. INMARSAT Channel

```
          ************** QRC ********************

 # errors corrected =   2
 there were no errors in QRC cw
 # errors corrected =   2
 success =   763
  you just completed superframe #   999
 # errors corrected =   2
 # errors corrected =   4
 fail =   236
 total errors in sf =   8
  number of 10ms fades in   1000   runs =   1842
  number of 20ms fades in   1000   runs =   254
  number of 40ms fades in   1000   runs =   103
  number of 100ms fades in   1000   runs =   87
  number of 200ms fades in   1000   runs =   24
  you just completed superframe #   1000
 iallerr=   3955   itotbitct=   143856  n =   1000
  the total number of failures =   236
  the total number of successes =   763
  This was a nogolay run
  This was a QRC BE count run
  This run used fading (1=yes,0=no)   1
  s/n during fade (dB) =   -24.0000
  s/n during non-fade (dB) =   99.0000


  ***************** Soft Decision Golay **************

 success =   746
  you just completed superframe #   999
 success =   747
  number of 10ms fades in   1000   runs =   1909
  number of 20ms fades in   1000   runs =   239
  number of 40ms fades in   1000   runs =   129
  number of 100ms fades in   1000   runs =   86
  number of 200ms fades in   1000   runs =   32
  you just completed superframe #   1000
  the total number of failures =   252
```

```
the total number of successes =   747
This was a soft golay run
This run used fading (1=yes,0=no)   1
s/n during fade (dB) =   -24.0000
s/n during non-fade (dB) =    99.0000
```

B. Gaussian Channel

```
*************** No Code **************

errors in   100   bits =   18
errors in   3000   bits =   337
errors in   3000   bits =   352
errors in   3000   bits =   364
errors in   3000   bits =   367
 you just completed superframe #   200
 the total number of failures =   198
 the total number of successes =   0
 This was a nogolay run
 This run used fading (1=yes,0=no)   0
 s/n during fade (dB) =   -24.0000
 s/n during non-fade (dB) =   3.00000


errors in   100   bits =   11
errors in   3000   bits =   249
errors in   3000   bits =   268
errors in   3000   bits =   265
errors in   3000   bits =   262
 you just completed superframe #   200
 the total number of failures =   196
 the total number of successes =   1
 This was a nogolay run
 This run used fading (1=yes,0=no)   0
 s/n during fade (dB) =   -24.0000
 s/n during non-fade (dB) =   4.00000


errors in   100   bits =   7
errors in   3000   bits =   179
errors in   3000   bits =   182
errors in   3000   bits =   175
errors in   3000   bits =   176
 you just completed superframe #   200
 the total number of failures =   197
 the total number of successes =   2
 This was a nogolay run
 This run used fading (1=yes,0=no)   0
 s/n during fade (dB) =   -24.0000
 s/n during non-fade (dB) =   5.00000
```

```
errors in   100   bits =   4
errors in   3000   bits =   125
errors in   3000   bits =   128
errors in   3000   bits =   103
errors in   3000   bits =   116
 you just completed superframe #   200
 the total number of failures =   192
 the total number of successes =   7
 This was a nogolay run
 This run used fading (1=yes,0=no)   0
 s/n during fade (dB) =   -24.0000
 s/n during non-fade (dB) =   6.00000
```

```
********** Hard Decision Golay *********

  errors in   100   bits =   14
  errors in   3000   bits =   240
  errors in   3000   bits =   277
  errors in   3000   bits =   268
  errors in   3000   bits =   278
   you just completed superframe #   200
   the total number of failures =   171
   the total number of successes =   26
   This was a hard golay run
   This run used fading (1=yes,0=no)   0
   s/n during fade (dB) =   -24.0000
   s/n during non-fade (dB) =    3.00000


  errors in   100   bits =   1
  errors in   3000   bits =   111
  errors in   3000   bits =   146
  errors in   3000   bits =   145
  errors in   3000   bits =   136
   you just completed superframe #   200
   the total number of failures =   123
   the total number of successes =   72
   This was a hard golay run
   This run used fading (1=yes,0=no)   0
   s/n during fade (dB) =   -24.0000
   s/n during non-fade (dB) =    4.00000


  errors in   100   bits =   0
  errors in   3000   bits =   41
  errors in   3000   bits =   52
  errors in   3000   bits =   48
  errors in   3000   bits =   36
   you just completed superframe #   200
   the total number of failures =   57
   the total number of successes =   140
   This was a hard golay run
   This run used fading (1=yes,0=no)   0
   s/n during fade (dB) =   -24.0000
   s/n during non-fade (dB) =    5.00000
```

```
 errors in   100   bits =   0
 errors in   3000   bits =   5
 errors in   3000   bits =   0
 errors in   3000   bits =   4
 errors in   3000   bits =   7
  you just completed superframe #   200
  the total number of failures =   13
  the total number of successes =   186
  This was a hard golay run
  This run used fading (1=yes,0=no)   0
  s/n during fade (dB) =   -24.0000
s/n during non-fade (dB) =    6.00000
```

```
********** Soft Decision Golay *******

errors in   100   bits =   10
errors in   3000   bits =   146
errors in   3000   bits =   192
errors in   3000   bits =   172
errors in   3000   bits =   182
 you just completed superframe #   200
 the total number of failures =   135
 the total number of successes =   62
 This was a soft golay run
 This run used fading (1=yes,0=no)   0
 s/n during fade (dB) =   -24.0000
 s/n during non-fade (dB) =    3.00000


errors in   100   bits =   0
errors in   3000   bits =   62
errors in   3000   bits =   75
errors in   3000   bits =   88
errors in   3000   bits =   68
 you just completed superframe #   200
 the total number of failures =   77
 the total number of successes =   122
 This was a soft golay run
 This run used fading (1=yes,0=no)   0
 s/n during fade (dB) =   -24.0000
 s/n during non-fade (dB) =    4.00000


errors in   100   bits =   0
errors in   3000   bits =   18
errors in   3000   bits =   13
errors in   3000   bits =   24
errors in   3000   bits =   10
 you just completed superframe #   200
 the total number of failures =   24
 the total number of successes =   175
 This was a soft golay run
 This run used fading (1=yes,0=no)   0
 s/n during fade (dB) =   -24.0000
 s/n during non-fade (dB) =    5.00000
```

```
errors in   100   bits =   0
errors in   3000   bits =   0
errors in   3000   bits =   0
errors in   3000   bits =   0
errors in   3000   bits =   7
 you just completed superframe #   200
 the total number of failures =   5
 the total number of successes =   194
 This was a soft golay run
 This run used fading (1=yes,0=no)   0
 s/n during fade (dB) =   -24.0000
 s/n during non-fade (dB) =   6.00000
```

C. Constant Burst Width Channel

```
KEY:

fade widths (120, 240, 480, 1200, 2400) correspond to
burst widths (10, 20, 40, 100, 200) milliseconds.

************* No Code ******************

  errors in   100   bits =   4
  errors in   3000   bits =   101
  errors in   3000   bits =   95
  errors in   3000   bits =   86
  errors in   3000   bits =   70
   you just completed superframe #   200
   the total number of failures =   106
   the total number of successes =   93
   This was a nogolay run
   This run used fading (1=yes,0=no)   1
  fading width, bwidth =   120
   s/n during fade (dB) =   -24.0000
   s/n during non-fade (dB) =   99.0000


  errors in   100   bits =   7
  errors in   3000   bits =   178
  errors in   3000   bits =   190
  errors in   3000   bits =   188
  errors in   3000   bits =   102
   you just completed superframe #   200
   the total number of failures =   114
   the total number of successes =   85
   This was a nogolay run
   This run used fading (1=yes,0=no)   1
  fading width, bwidth =   240
   s/n during fade (dB) =   -24.0000
   s/n during non-fade (dB) =   99.0000


  errors in   100   bits =   0
  errors in   3000   bits =   283
  errors in   3000   bits =   265
  errors in   3000   bits =   324
  errors in   3000   bits =   218
   you just completed superframe #   200
```

```
 the total number of failures =   123
 the total number of successes =   74
 This was a nogolay run
 This run used fading (1=yes,0=no)   1
fading width, bwidth =   480
 s/n during fade (dB) =   -24.0000
 s/n during non-fade (dB) =    99.0000


errors in   100   bits =   29
errors in   3000   bits =   472
errors in   3000   bits =   606
errors in   3000   bits =   482
errors in   3000   bits =   462
 you just completed superframe #   200
 the total number of failures =   135
 the total number of successes =   62
 This was a nogolay run
 This run used fading (1=yes,0=no)   1
fading width, bwidth =   1200
 s/n during fade (dB) =   -24.0000
 s/n during non-fade (dB) =    99.0000


errors in   100   bits =   26
errors in   3000   bits =   798
errors in   3000   bits =   816
errors in   3000   bits =   852
errors in   3000   bits =   883
 you just completed superframe #   200
 the total number of failures =   156
 the total number of successes =   39
 This was a nogolay run
 This run used fading (1=yes,0=no)   1
fading width, bwidth =   2400
 s/n during fade (dB) =   -24.0000
 s/n during non-fade (dB) =    99.0000
```

```
************ Hard Decision Golay **********

 errors in   100   bits =   0
 errors in   3000   bits =   10
 errors in   3000   bits =   13
 errors in   3000   bits =   7
 errors in   3000   bits =   13
  you just completed superframe #   200
  the total number of failures =   11
  the total number of successes =   188
  This was a hard golay run
  This run used fading (1=yes,0=no)   1
 fading width, bwidth =   120
  s/n during fade (dB) =   -24.0000
  s/n during non-fade (dB) =   99.0000


 errors in   100   bits =   0
 errors in   3000   bits =   25
 errors in   3000   bits =   40
 errors in   3000   bits =   58
 errors in   3000   bits =   18
  you just completed superframe #   200
  the total number of failures =   41
  the total number of successes =   158
  This was a hard golay run
  This run used fading (1=yes,0=no)   1
 fading width, bwidth =   240
  s/n during fade (dB) =   -24.0000
  s/n during non-fade (dB) =   99.0000


 errors in   100   bits =   0
 errors in   3000   bits =   270
 errors in   3000   bits =   257
 errors in   3000   bits =   234
 errors in   3000   bits =   305
  you just completed superframe #   200
  the total number of failures =   102
  the total number of successes =   97
  This was a hard golay run
  This run used fading (1=yes,0=no)   1
 fading width, bwidth =   480
  s/n during fade (dB) =   -24.0000
```

```
 s/n during non-fade (dB) =    99.0000


errors in   100   bits =   0
errors in   3000   bits =   698
errors in   3000   bits =   543
errors in   3000   bits =   733
errors in   3000   bits =   616
 you just completed superframe #   200
 the total number of failures =   151
 the total number of successes =   48
 This was a hard golay run
 This run used fading (1=yes,0=no)   1
fading width, bwidth =   1200
 s/n during fade (dB) =   -24.0000
 s/n during non-fade (dB) =    99.0000


errors in   100   bits =   14
errors in   3000   bits =   739
errors in   3000   bits =   972
errors in   3000   bits =   986
 you just completed superframe #   200
 the total number of failures =   133
 the total number of successes =   19
 This was a hard golay run
 This run used fading (1=yes,0=no)   1
fading width, bwidth =   2400
 s/n during fade (dB) =   -24.0000
 s/n during non-fade (dB) =    99.0000
```

```
********** Soft Decision Golay *********

 errors in   100   bits =   0
 errors in   3000   bits =   0
 errors in   3000   bits =   0
 errors in   3000   bits =   0
 errors in   3000   bits =   0
  you just completed superframe #   200
  the total number of failures =   2
  the total number of successes =   197
  This was a soft golay run
  This run used fading (1=yes,0=no)   1
 fading width, bwidth =   120
  s/n during fade (dB) =   -24.0000
  s/n during non-fade (dB) =   99.0000


 errors in   100   bits =   0
 errors in   3000   bits =   0
 errors in   3000   bits =   76
 errors in   3000   bits =   10
 errors in   3000   bits =   26
  you just completed superframe #   200
  the total number of failures =   21
  the total number of successes =   178
  This was a soft golay run
  This run used fading (1=yes,0=no)   1
 fading width, bwidth =   240
  s/n during fade (dB) =   -24.0000
  s/n during non-fade (dB) =   99.0000


 errors in   100   bits =   0
 errors in   3000   bits =   111
 errors in   3000   bits =   137
 errors in   3000   bits =   133
 errors in   3000   bits =   153
  you just completed superframe #   200
  the total number of failures =   60
  the total number of successes =   139
  This was a soft golay run
  This run used fading (1=yes,0=no)   1
 fading width, bwidth =   480
  s/n during fade (dB) =   -24.0000
```

```
 s/n during non-fade (dB) =    99.0000


errors in   100   bits =   0
errors in   3000   bits =   412
errors in   3000   bits =   521
errors in   3000   bits =   647
errors in   3000   bits =   509
 you just completed superframe #   200
 the total number of failures =   133
 the total number of successes =   66
 This was a soft golay run
 This run used fading (1=yes,0=no)   1
fading width, bwidth =   1200
 s/n during fade (dB) =   -24.0000
 s/n during non-fade (dB) =    99.0000


errors in   100   bits =   8
errors in   3000   bits =   769
errors in   3000   bits =   711
errors in   3000   bits =   976
errors in   3000   bits =   757
 you just completed superframe #   200
 the total number of failures =   160
 the total number of successes =   39
 This was a soft golay run
 This run used fading (1=yes,0=no)   1
fading width, bwidth =   2400
 s/n during fade (dB) =   -24.0000
 s/n during non-fade (dB) =    99.0000
```

Hamming Codeword Interleaving Table

CW1	CW2	CW3	CW4	CW5	CW6	CW7	CW8	CW9
721	731	751	761	781	791	811	821	841
991	1001	1021	1031	1051	1061	1081	1091	1111
1261	1271	1291	1301	1321	1331	1351	1361	1381
1531	1541	1561	1571	1591	1601	1621	1631	1651
1801	1811	1831	1841	1861	1871	1891	1901	1921
2071	2081	2101	2111	2131	2141	2161	2171	2191
2341	2351	2371	2381	2401	2411	2431	2441	2461
2611	2621	2641	2651	2671	2681	2701	2711	2731

CW10	CW11	CW12	CW13	CW14	CW15	CW16	CW17	CW18
851	871	881	901	911	931	941	961	971
1121	1141	1151	1171	1181	1201	1211	1231	1241
1391	1411	1421	1441	1451	1471	1481	1501	1511
1661	1681	1691	1711	1721	1741	1751	1771	1781
1931	1951	1961	1981	1991	2011	2021	2041	2051
2201	2221	2231	2251	2261	2281	2291	2311	2321
2471	2491	2501	2521	2531	2551	2561	2581	2591
2741	2761	2771	2791	2801	2821	2831	2851	2861

Golay Codeword Interleaving Table

CW1	CW2	CW3	CW4	CW5	CW6
721	751	781	811	841	871
731	761	791	821	851	881
901	931	961	991	1021	1051
911	941	971	1001	1031	1061
1081	1111	1141	1171	1201	1231
1091	1121	1151	1181	1211	1241
1261	1291	1321	1351	1381	1411
1271	1301	1331	1361	1391	1421
1441	1471	1501	1531	1561	1591
1451	1481	1511	1541	1571	1601
1621	1651	1681	1711	1741	1771
1631	1661	1691	1721	1751	1781
1801	1831	1861	1891	1921	1951
1811	1841	1871	1901	1931	1961
1981	2011	2041	2071	2101	2131
1991	2021	2051	2081	2111	2141
2161	2191	2221	2251	2281	2311
2171	2201	2231	2261	2291	2321
2341	2371	2401	2431	2461	2491
2351	2381	2411	2441	2471	2501
2521	2551	2581	2611	2641	2671
2531	2561	2591	2621	2651	2681
2701	2731	2761	2791	2821	2851
2711	2741	2771	2801	2831	2861

QRC Codeword Interleaving Table

CW1	CW2	CW3
721	781	841
731	791	851
751	811	871
761	821	881
1081	1141	1201
1091	1151	1211
1111	1171	1231
1121	1181	1241
1441	1501	1561
1451	1511	1571
1471	1531	1591
1481	1541	1601
1801	1861	1921
1811	1871	1931
1831	1891	1951
1841	1901	1961
2161	2221	2281
2171	2231	2291
2191	2251	2311
2201	2261	2321
2521	2581	2641
2531	2591	2651
2551	2611	2671
2561	2621	2681

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