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HADAMARD SOURCE ENCODING TECHNIQUES APPLIED TO APOLLO
TELEMETRY LINKS: AN EVALUATION

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ABSTRACT

The effort described in this paper is an
investigation of the possible improvement
in performance of the Apollo Unified
S-Band Telemetry links due to the use of
the Hadamard transform as a means of
source encoding. Both rapidly and slowly
varying telemetry signals were considered
and three sizes of the Hadamard matrix
were used. Results indicate that as much
as 3-db improvement in system performance
may be obtained in systems operating at a
2% RMS error level.

INTRODUCTION

In recent years, the practicality of
space communications, both for manned
space research and unmanned communications
satellites, has become evident. The
rapidly increasing amount of information
to be transmitted is placing arduous
demands on the system channel capacity.
Also, the prospect of future manned deep
space probes requires improved system
signal-to-noise ratios. Data compression
and channel encoding techniques have been
developed to help meet these more rigid
requirements [1], [2].

Recent developments of "fast" orthogonal
transforms have provided new concepts of
source encoding as a means of reducing
bandwidth and carrier-power requirements
for space communication systems. Some of
the more promising transforms include the
Fourier, Haar, Hadamard and Karhunin-Loeve
transforms, [3], [4], [5].

The effort described in this paper is an
investigation of the possible improvement
of the Apollo Unified S-Band Telemetry
Links due to the use of the Hadamard
transform as a means of source encoding.
Actual command and service module-ground
station communication equipment with a
simulated RF link was used in the test.
These facilities are located at the Manned
Spacecraft Center. Both slowly changing
and rapidly changing digital signals were

investigated. Hadamard matrices of orders
4, 16, and 64 were used in obtaining the
transformations.

It is realized that the resulting system
is not "optimal" in any manner, but the
results do reflect the advantages of
using the Hadamard technique without
redesign of other system components.
Areas where system changes could result in
significant additional improvement in
performance are also revealed.

Section II gives a brief summary of the
Hadamard transform. The experimental
study is described in Section III. The
results of this study are shown in Section
IV and conclusions are presented in
Section V.

THE HADAMARD TRANSFORM

Given a one dimensional signal, $f(t)$, its
finite sampled transform can be represent-
ed as

$$Y = HX \qquad (1)$$

where X is an $N \times 1$ vector of signal
samples of $f(t)$, H is an $N \times N$ transforma-
tion matrix and Y is an $N \times 1$ vector of
transformed samples. One element of Y is

$$Y(n) = \sum_{k=0}^{N-1} x (k\Delta T) \, h_{kn} \qquad (2)$$

For orthogonal transforms, the signal
vector elements are recovered by

$$X(k\Delta T) = \sum_{n=0}^{N-1} Y(n) \, h_{kn} \qquad (3)$$

In eqs. (2) and (3), h_{kn} is an element of
the matrix H. If the element h_{kn} is
defined as the inner product

$$h_{kn} = <Wal(k,\xi), \ \delta(\xi - \frac{n}{N\Delta T})> \qquad (4)$$

then the resulting matrix is the Hadamard
matrix and the transformation is known as

the Hadamard Transform. In eq. (4), the Wal (k,θ) represent the set of Walsh functions, the first eight of which are shown in Figure 1 [3]. These are overlapping rectangular functions which are orthogonal in the normalized interval $0 < \xi < 1$. Examples of three Hadamard matrices are shown in Figure 2. Matrices of higher order are easily constructed from lower order matrices. Each matrix is comprised of only the elements +1 and -1. Further, all rows and columns are mutually orthogonal and any two rows or any two columns may be interchanged without affecting the orthogonality property.

Except for a constant factor equal to the rank of the matrix, the Hadamard matrix is its own inverse. Thus, to recover the original vector X:

$$X = H^{-1} \quad Y = \frac{1}{N} HY$$

This expression is signigicant from the standpoint that implementation of the Hadamard transform technique requires development of only one piece of hardware for both the transform and inverse transform processes.

The most significant advantage of the Hadamard matrix, however, is its ability to effect a transform of a signal while requiring only the operations of additions and subtractions.

EXPERIMENTAL STUDY

The system diagram for this study is shown in Figure 3. One-hundred ninety-six signal samples were generated to correspond to the command and service module low bit rate telemetry format of 200 words which includes four frame synchronization words. Two types of signal samples were generated. The first type consisted of 196 samples evenly spaced over one cycle of a sine wave. This signal was chosen to represent slowly changing telemetry data such as battery voltage, vehicle velocity, etc. The second signal type was 196 data points chosen by sampling a random variable uniformly distributed over the interval (0,1). This type of course represents rapidly or randomly changing telemetry signals.

The signals were processed in three phases. The first phase was accomplished on the Univac 1108 Computing System and consisted of signal generation, Hadamard transformation of the signal if applicable, and pulse code modulation (PCM) of the transformed and untransformed signals. An eight bit uniform quantization method was used for the PCM. This was accomplished by generating 256 evenly spaced levels between the maximum and minimum values of input data and then assigning each data

point to the closest level. Hence for each data point, an 8-bit binary number between 0 and 255 is generated. The sequence of 196 eight-bit numbers and four eight-bit synch words from one 1600 bit frame. This frame is supplied to the second phase of the system which is detailed in Figure 4.

Actual spacecraft-ground station communication equipment was used in phase two. The RF path from spacecraft to ground station was of course simulated but is accurately calibrated so that the simulation closely resembled actual mission conditions. Data was transmitted for three different system bit error rates (BER). Ten thousand frames (16 million bits) were examined for 10^{-4} BER; 5000 frames for 10^{-3} BER; and 1000 frames for 10^{-2} BER. The PCM bit synchronizer output was recorded on magnetic tape for use in phase three.

The Univac 1108 computer was again utilized in the last step of the signal processing. Using the reference levels from phase I, the PCM signal recorded in phase II was decoded and the inverse transformation performed if necessary. The resulting estimates of the original signal were then compared with the actual values and the per cent RMS error rate per word was calculated.

For a standard of comparison, the signals were processed in the normal manner through the system and the RMS error calculated. The signals were then Hadamard transformed and processed in the same manner. Three sizes of the matrix (N=4, N=16, N=64) were considered in each case. Hence, a total of eight different bit streams were transmitted for each of the three bit error rates.

RESULTS

Per cent RMS error vs bit error rate for slowly changing (sine wave) data is shown in Figure 5. Two cases are depicted; untransformed data and data transformed by the Hadamard technique with N=4. The data from runs with N=16 and N=64 were so close to the N=4 case as to be indistinguishable on a graph. Surprisingly, the N=16 and N=64 data were slightly worse than the N=4 case.

Figure 6 depicts the RMS error comparison for the fast changing (random) input signal. Again the N=16 and N=64 cases were very close, but slightly worse than for N=4.

Curves relating bit error rate and signal-to-noise ratio for PSK matched filter detection are well established [6]. Hence,

using this known relation and the information from Figures 5 and 6, one can construct the comparison shown in Figure 7. Improvement of system performance in db is plotted as a function of % RMS error. For example, if the system normally operates at a 2% RMS error level and slowly varying data is considered, then the required system signal-to-noise ratio can be reduced 2.8 db by using the Hadamard transform technique.

It is significant to note in Figures 5 and 6 that at low bit error rates (≈ 10⁻⁴) the conventional system outperforms the Hadamard system. This phenomenon can be attributed to the quantization scheme used. It is possible to show that the quantization error for the Hadamard system is equal to the quantization error of the conventional system plus a positive quantity that is a function of system parameters. Hence, for low bit errors when quantization noise becomes significant the performance of the Hadamard system should be worse. However, as the bit error rate increases and the channel noise becomes the major contributor to RMS error, the noise distributing properties of the Hadamard transform provides significant improvement and the overall performance of the Hadamard system as compared to the conventional system increases.

Also the RMS error of the Hadamard system increases as the matrix size N increases if there is no channel noise (S|N = ∞). This may explain why the performance of the N=16 and N=64 cases were slightly worse than the N=4 case.

CONCLUSIONS

It has been shown experimentally that Hadamard transform techniques can provide significant improvement in Apollo Unified S-Band System performance, especially if the input data is changing slowly. However, for low bit error rates uniform quantizing, the conventional system is better. The study was made under the constraint that no changes be made in the existing Apollo System except the introduction of the transform itself. It is felt that significant additional improvement could be obtained using other more nearly optimum quantizing schemes.

As a sidelight, it was noted that a 4:1 data compression could be accomplished by transmitting only transform values greater than zero (approximately) and the position of these values.

REFERENCES

(1) Kortman, M. C., "Redundancy Reduction A Practical Method of Data Compression," Proceedings of IEEE, vol. 55, no. 3, March 1967, pp. 253-263.

(2) Andrews, C. A., J. M. Davies, and G. R. Schwarz, "Adaptive Data Compression," Proceedings of IEEE, vol. 55, no. 3, March 1967.

(3) Harmuth, H. F., Transmission of Information by Orthogonal Functions, 2nd Edition, Springer-Verlag, New York, 1970.

(4) Pratt, W. K. and H. C. Andrews, "Application of Fourier-Hadamard Transformation to Bandwidth Compression," Symposiu, on Picture Bandwidth Compression, M.I.T., Cambridge, Mass., April, 1969.

(5) Fukunaga, K. and W. L. G. Koonty, "Application of the Karhunen-Loeve Expansion to Feature Selection and Ordering", IEEE Transactions on Computers, vol. C-19, no. 4, pp. 311-318, April, 1970.

(6) Schwarts, M., W. R. Bennett, S. Stein, Communication Systems and Techniques, McGraw-Hill, New York, 1966, p. 77.

(7) Pratt, W. K., Kane and H. C. Andrews, "Hadamard Transform Image Coding", Proceedings of the IEEE, vol. 57, no. 1, January, 1969.
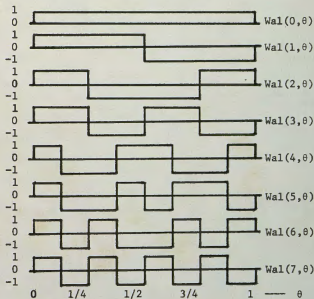
Fig. 1 First Eight Walsh Functions

$$\underline{N=2} \quad H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$\underline{N=4} \quad H_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} = \begin{bmatrix} H_2 & H_2 \\ H_2 & -H_2 \end{bmatrix}$$

$$\underline{N=8} \quad H_8 = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 \end{bmatrix} = \begin{bmatrix} H_4 & H_4 \\ H_4 & -H_4 \end{bmatrix}$$

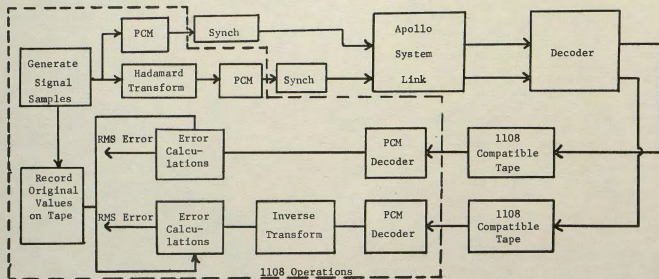Fig. 2 Examples of Hadamard Matrices
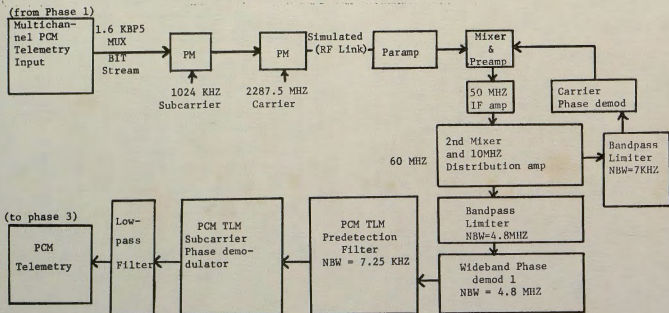

Fig. 3: System Diagram for Hadamard Transform Study

Fig. 4 Block Diagram of Phase Two Signal Processor

Fig. 5: % RMS Error vs Channel BER for Slowly Varying Data

Fig. 7: % RMS error vs. DB Improvement

Fig. 6: % RMS Error vs BER for Rapidly Varying Signal