AN EFFICIENT GOLAY CODEC FOR
MIL-STD-188-141A AND FED-STD-1045

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Introduction

The new government standards for Automatic Link Establishment (ALE) in High Frequency (HF) radio systems [1, 2] specify the use of an extended (24,12) Golay block code for forward error correction (FEC). The purpose of this report is to discuss a fast codec (encoder and decoder) for this code, which achieves its high speed by keeping about 20 KB of tables in memory. The general outline of this codec is suggested in the standards; this report provides some implementation details which we did not include in the standards, including the technique for varying the error-correction power of the codec, along with a mathematical justification of the techniques employed.

The Extended (24,12) Golay Code

The code specified is a (24,12) block code; i.e., it encodes 12 data bits to produce 24-bit code words. It is furthermore a systematic code, meaning that the 12 data bits are present in unchanged form in the code word. The generator polynomial for this code is: $g(x) = x^{11} + x^9 + x^7 + x^6 + x^5 + x + 1$, with the corresponding generator matrix shown in Figure 1.

The minimum Hamming distance between any two code words (the number of bits by which any pair of code words differs) is 8, giving this code the power to detect up to 7 errors in each code word (and correct none), correct up to 3 while detecting 4, or any intermediate combination. These modes may be listed as (0,7), (1,6), (2,5), and (3,4), where the first number indicates the number of errors which may be corrected, and the second the number of errors which will be detected by each mode.

1

$$
G \ = \ \begin{bmatrix}
100 & 000 & 000 & 000 & : & 101 & 011 & 100 & 011 \\
010 & 000 & 000 & 000 & : & 111 & 110 & 010 & 010 \\
001 & 000 & 000 & 000 & : & 110 & 100 & 101 & 011 \\
000 & 100 & 000 & 000 & : & 110 & 001 & 110 & 110 \\
000 & 010 & 000 & 000 & : & 110 & 011 & 011 & 001 \\
000 & 001 & 000 & 000 & : & 011 & 001 & 101 & 101 \\
000 & 000 & 100 & 000 & : & 001 & 100 & 110 & 111 \\
000 & 000 & 010 & 000 & : & 101 & 101 & 111 & 000 \\
000 & 000 & 001 & 000 & : & 010 & 110 & 111 & 100 \\
000 & 000 & 000 & 100 & : & 001 & 011 & 011 & 110 \\
000 & 000 & 000 & 010 & : & 101 & 110 & 001 & 101 \\
000 & 000 & 000 & 001 & : & 010 & 111 & 000 & 111
\end{bmatrix}
$$

Figure 1: Generator Matrix

In matrix formulation, the code word $\underline{u}$ corresponding to a data word $\underline{m}$ is found by the product $\underline{u} \ = \ \underline{m} \cdot G$. Note that the left half of the generator matrix G is simply a 12 x 12 identity matrix I_{12}; the right half of G generates the parity check bit portion of the code word, and is commonly called the P matrix.

The introduction of errors in the communication channel is typically modeled as an error vector $\underline{e}$ which is added (modulo 2) to the code word originally sent to produce a received word $\underline{r} \ = \ \underline{e} + \underline{u}$. In block codes such as this, the decoder computes a *syndrome* $\underline{s} \ = \ \underline{r} \cdot H^T$, where H is the parity check matrix derived from G:

$$H \ = \ [P^T \ I_{12}]$$

and the superscript T (as in H^T and P^T) indicates matrix transposition. This vector-matrix multiplication simply computes the parity check bits for the received data bits, and adds them (modulo 2) with the received parity check bits, giving a 0 result if a valid code word is received.

Encoder

Many computational tasks have a range of possible solution techniques which allow a system designer to trade memory for speed and vice versa. In the case of an encoder for the code considered here, we can compute the code word corresponding to a data word either by performing the vector-matrix product described above, or by precomputing this product for all data words (2^{12} in number) and storing these products in a table. The former approach requires storage only for the P matrix, and proceeds by multiplying $\underline{m}$ by P (twelve 12-bit inner products) and concatenating the result with $\underline{m}$.

The latter technique requires storage for 2^{12} 12-bit products, but is somewhat faster, requiring only a table lookup and concatenation. This table-lookup technique is the one chosen for our high-speed codec.

Decoder

A range of time-memory tradeoffs is available for the decoder. Because of the small size of the code word, we can use the standard array technique [3] to design a fast and relatively straightforward decoder. Such a decoder is based on a conceptual table of all possible received words. This *standard array* is formed as follows:

- Each row in the table is called a *coset*.

- The first entry in each row is called the *coset leader*.

- The rows correspond one-to-one to the syndromes.

- The first row (row 0) contains all of the valid code words, corresponding to syndrome 0.

- Each column in the table contains exactly one valid code word (in row 0).

- The first column contains the all-zero code word in row 0.

- The coset leader of row i is the error pattern $\underline{e}$ which, added to the code word in column j, produces the received word located at (i, j).

- Coset leaders are chosen so as to include all correctable error patterns. In the case of our extended (24, 12) Golay code, we have $2^{12} = 4096$ coset leaders, including the all 0 pattern in row 0, all 24 single-bit-error patterns, all 276 two-bit-error patterns, all 2024 three-bit-error patterns, and 1171 of the possible 10,626 four-bit-error patterns.

If the coset leaders of the standard array are ordered by increasing syndrome value, the resulting table is sufficient to decode received words. It is used as follows:

1. The syndrome of each received word is computed.

2. This syndrome is used to select the appropriate coset leader.

3. If the coset leader selected corresponds to a correctable error pattern, that pattern is added (modulo 2) with the received word, and the corrected data word is the output of the decoder; otherwise, the decoder indicates the presence of an uncorrectable error.

To implement a decoder with selectable error correction power, it is sufficient to store (along with the table of error patterns) a table of the Hamming weights of the coset leaders, again indexed by syndrome. Let the selected error correcting power be denoted C. Then step 3 of the decoding procedure above is modified to perform correction only if the weight of the selected pattern is less than or equal to C, and to indicate an uncorrectable error otherwise.

That this simple modification is sufficient to correctly perform all modes of the decoder may seem surprising. For instance, the question may arise, "When switching from (3,4) mode to (0,7), why should I believe that this decoder will now be able to detect all error patterns of weight 7, when it was only required to detect patterns of weight 4 before?" The range of all such errors that this decoder could make are analyzed in the following section.

Decoder Analysis

Before proceeding to the exhaustive analysis of possible faults in this decoder, some aspects of its structure need to be discussed. First, since the minimum distance of the extended (24, 12) Golay code is 8, the minimum weight of any error pattern which would transform a valid code word into another valid code word is 8. Thus, the minimum weight of any non-zero code word is 8.

Second, each coset leader has the minimum weight of all error patterns in its coset: all other coset members are produced by adding the coset leader to a non-zero code word, and therefore have weight of at least (8 – weight of coset leader). Because no coset leader has weight greater than four, all coset leaders have minimum weights within their cosets (though not uniquely, in the case of weight 4 coset leaders).

The range of possible errors for this decoder is as follows:

1. An error-free word was received, but the decoder made an erroneous correction.

2. An error-free word was received, but the decoder reported a non-correctable error.

3. A correctable error pattern was received, but treated as error-free.

4. A detectable, non-correctable error pattern was received, but not detected.

5. A correctable error pattern was received, but the decoder reported a non-correctable error.

6. A detectable, non-correctable error pattern was received, but the decoder attempted correction.

In cases 1 and 2, the syndrome will be 0, which only occurs for error-free words. The decoder will always pass these words through unchanged (i.e., it will add the all 0 coset leader for syndrome 0).

Cases 3 and 4 produce non-zero syndromes, and are therefore always detected as containing errors.

Case 5 requires that the weight of the error pattern which occurred be less than the weight of the coset leader of the syndrome produced by that error pattern. However, as noted above, the coset leader for each syndrome never has larger weight than any error pattern which can produce that syndrome.

In case 6, we complete the answer to the question raised at the end of the last section, which was partially answered by case 4. The basic question is this: do any detectable, non-correctable error patterns produce syndromes whose coset leader weights w_i would cause inappropriate actions? This would be the case if, for example, an error pattern of weight 6 or less has $w_i = 1$: when in (1,6) mode, this error pattern should be detected as uncorrectable, but the weight of the coset leader would cause an erroneous correction. In general, this problem will occur if a coset contains members (other than the coset leader) with weights less than $8 - w_i$. However, we noted above that the weights of all coset members other than the coset leader are at least $8 - w_i$, so this condition cannot occur.

Therefore, we conclude that none of these faults can occur in any of the operating modes of this decoder. An exhaustive search of the standard array used to produce the codec described in the Appendix verified that none of these cases can occur.

REFERENCES

[1] **MIL-STD-188-141A**, *Interoperability and Performance Standards for Medium and High Frequency Radio Equipment*, U.S. Army Information Systems Engineering Command, 1988.

[2] **FED-STD-1045**, *Telecommunications: HF Radio Automatic Link Establishment*, General Services Administration, 1990.

[3] Shu Lin, *An Introduction to Error-Correcting Codes*, Prentice-Hall, Englewood Cliffs, NJ, 1970. (see p. 47)

APPENDIX A

A C LANGUAGE IMPLEMENTATION OF THE
EFFICIENT GOLAY CODEC

The following pages contain C routines to implement the extended (24,12) Golay codec described in this report, followed by the tables used by these routines. Note the following:

encode()   The encoder uses a 12-bit lookup table (rather than 24) to avoid wasting memory to store the input data bits, which are reproduced unchanged as the most significant bits of the code word. The encode() function is implemented as a macro that shifts the data bits into position and appends the parity check bits from the table.

encode_tab.h The table used by encode() is contained in this file, which is listed immediately following the code. The table is called enc[] in the code.

errwt.h   The error weight table used by decode() is contained in this file, which immediately follows encode_tab.h. The table is called wt[] in the code.

errpat.h   The error pattern table used by decode() is contained in this file, which immediately follows errwt.h. The table is called e[] in the code.

These files are available from NMSU at no charge. Send a formatted floppy and a return mailer with your request to the following address:

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```c
/*  Golay.c          FEC routines for MIL/FED std ALE          eej      */


/********************    GOLAY ENCODER MODULE    ********************/

#include "encode_table.h"    /* P matrix "int enc[4096] = { ... }" */

#define encode(x) (((long)x<<12)|enc[x])

void Golay (w, G)                /* encode a 24-bit ALE word,        */
long w, G[];                     /* producing two 24-bit Golay words */
{
    G[0] = encode(w >> 12);
    G[1] = encode(w & 07777) ^ 07777;   /* invert B word check bits */
}


/********************    GOLAY DECODER MODULE    ********************/

#include "errwt.h" /* error weight matrix "int wt[4096] = { ... }" */
#include "errpat.h"/* error pattern matrix "int e[4096] = { ... }" */

#define ERROR_DETECTED -1

int errwt(w)
long w;
{
    register int i;

    i = (encode(w>>12) ^ w) & 07777;
    return (wt[i]);
}

long decode(w, power)              /* decode one 24-bit Golay word */
long w, power;
{
    register int i;

    if (errwt(w) > power) return (ERROR_DETECTED);
    i = (encode(w>>12) ^ w) & 07777;
    return (w>>12 ^ e[i]);
}

long DeGolay (G, power)          /* decode two 24-bit Golay words */
long G[], power;                 /* to yield one 24-bit ALE word. */
{
    long temp;

    temp = decode(G[1], power);
    if (temp > -1)
      return ((decode(G[0], power) << 12) | (temp & 07777));
    else return (-1);
}
```

8

```
int enc[4096] = { 00000, 02707, 05615, 07112, 01336, 03431, 04523, 06224,
                  02674, 00173, 07061, 05766, 03542, 01245, 06357, 04450,
                  05570, 07277, 00365, 02462, 04646, 06141, 01053, 03754,
                  07304, 05403, 02511, 00216, 06032, 04735, 03627, 01120,
                  01467, 03360, 04272, 06575, 00751, 02056, 05144, 07643,
                  03213, 01514, 06406, 04301, 02125, 00622, 07730, 05037,
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                  06763, 04064, 03176, 01671, 07455, 05352, 02240, 00547,
                  03155, 01652, 06740, 04047, 02263, 00564, 07476, 05371,
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                  06425, 04322, 03230, 01537, 07713, 05014, 02106, 00601,
                  04251, 06556, 01444, 03343, 05167, 07660, 00772, 02075,
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