A basic single-chip building block for a RS decoder system is partitioned into a plurality of sections the first of which consists of a plurality of syndrome subcells each of which contains identical standard-basis finite-field multipliers that are programmable between 10-bit and 8-bit operation. A desired number of basic building blocks may be assembled to provide a RS decoder of any syndrome subcell size that is programmable between 10-bit and 8-bit operation.

5 Claims, 6 Drawing Sheets
Figure 1

Data Source

Transmitter

(7,1/2) Convolutional Encoder

(255, 223) RS Encoder

Channel

Receiver

(7,1/2) Viterbi Decoder

(255, 223) RS Decoder

Data Sink
FIG. 4

Cell 1
\[ \alpha_0 \]

Cell 2
\[ \alpha_1 \]

Cell m
\[ \alpha_m \]

Cell m-1
\[ \alpha_{m-1} \]

B SERIAL INPUT

A SERIAL LOAD

\[ f(x) \]

\[ C_0 \]

\[ f_0 \]

\[ C_i \]

\[ f_i \]

\[ G_1 \]

\[ x_1 \]

\[ G_2 \]

\[ x_2 \]
Single Chip VLSI Building Block

| 8 SYNDROME SUBCELLS           | 31 |
| 8 POLYNOMIAL EXPANSION       | 32 |
| 8 POWER EXPANSION SUBCELLS   | 33 |
| 8 POLYNOMIAL EVALUATION SUBCELLS | 34 |
| 8 MODIFIED EUCLIDEAN ALGORITHM SUBCELLS | 35 |
| MISCELLANEOUS CELLS          | 36 |

**FIG. 6**

8-BIT RS DECODER: 4 CHIPS

CHIP 1 → CHIP 2 → CHIP 3 → CHIP 4

10-BIT RS DECODER: 8 CHIPS

CHIP 8 ← CHIP 7 ← CHIP 6 ← CHIP 5

**FIG. 7**

**FIG. 8**

HOST COMPUTER

CONTROL MEMORY

INPUT MODULE → RS DECODER DATA PATH → OUTPUT MODULE
VLSI ARCHITECTURE FOR A REED-SOLOMON DECODER

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the Contractor has elected not to retain title.

TECHNICAL FIELD

This invention relates to a very large scale integration (VLSI) architecture for implementing Reed-Solomon decoders by replicating a single VLSI chip. Furthermore, this Reed-Solomon decoder capable of correcting both errors and erasures is programmable for operation at different symbol sizes between 8-bit and 10-bit.

BACKGROUND ART

A (255,223) 8-bit Reed-Solomon (RS) code in concatenation with a (7, 4) Viterbi-decoded convolutional code has been recommended by the CCSDS (Consultative Committee for Space Data System) as a standard coding system for down link DSN (Deep Space Network) telemetry system. FIG. 1 shows a CCSDS recommended DSN transmission system. This concatenated coding system provides a coding gain of about 2 dB over the (7, 4) Viterbi-decoded only system.

Software simulations show that a (1023, 959) code, when concatenated with a (15, 1/6) Viterbi-decoded convolutional code, provides another 2 dB coding gain over the standard system recommended by CCSDS. This additional coding gain may be needed for future deep space missions to save cost since coding is among 

The costs to design, fabricate and test VLSI-based systems increase drastically with the number of different chip types used. As an example, the (255, 223) error-correcting only RS decoder developed by the University of Idaho consists of four different types of VLSI chips, as just noted above. Assuming it takes 8 work-months to design and test a VLSI chip, which is a reasonable assumption for a VLSI chip of this complexity, four different chips require 32 work-months to develop. Furthermore, assuming it costs $80,000 to fabricate a VLSI chip of this complexity, the total VLSI chip fabrication cost of the above RS chips is $320,000. By utilizing the concept of the present invention, it takes only 8 work-months to design and test $80,000 fabrication cost to develop VLSI chips for the single chip to be replicated for an RS decoder system. Based on the above analysis, a single-chip type RS decoder system is expected to have a five fold cost savings compared to RS decoder systems using conventional partition schemes.

As noted hereinbefore, the (255, 223) 8-bit RS code has been recommended by the CCSDS as part of the standard coding scheme in the DSN telecommunication system. Software simulations also show the system performance improvement obtained by concatenating a (1023, 959) 10-bit RS decoder with a (15, 1/6) Viterbi decoded convolutional code. Therefore, there is a need for developing both 8-bit and 10-bit RS decoders for current and future uses. As a consequence, it is desirable to realize an RS decoder which is capable of being switched between 8-bit and 10-bit codes. The key in developing such an 8-bit and 10-bit switchable RS decoder is the development of an 8-bit and 10-bit switchable finite field multiplier which is the most frequently used functional building block in an RS decoder.

STATEMENT OF THE INVENTION

An object of this invention is to provide a standard-basis finite-field multiplier for a RS decoder system which is switchable between a first and a second symbol size. A further object is to provide an architecture for implementing a time-domain RS decoder that can correct both errors and erasures with a symbol size larger than the first symbol size by replication of a single VLSI chip using a programmable 8-bit/10-bit standard-basis finite-field multiplier for syndrome computation.

In accordance with the present invention, a standard-basis finite-field multiplier is provided for a Reed-Solomon decoder that can correct both errors and erasures with a symbol size of n+1 bits, where n+1 is larger than 8. The multiplier is comprised of n cells, each cell consisting of: three 1-bit registers f₀, cᵢ, and aᵢ, where i=0,1,2, ... , n+1; two AND gates G₁ and G₂; and two exclusive OR gates X₁ and X₂, except the first cell which has only one exclusive OR gate X₁. The 1-bit register aᵢ receives a multiplicand bit represented in the basis of {a₀, a₁, a₂, a₃, a₄, a₅, a₆, a₇, a₈}. It is multiplied by an input multiplier B in serial form b₀, b₁, b₂, b₃, b₄, b₅, b₆, b₇, b₈ through AND gate G₁ and fed to the next cell i+1 through the exclusive OR gate X₁ of cell i and the exclusive OR gate X₂ of cell i+1, except the last cell which feeds back through its exclusive OR gate X₁ directly to all cells through their AND gates G₂ for multiplication with an irreducible primitive polynomial f(X) of the field. The output of AND gate G₁ of each cell except the first cell where j=0, is combined with the output of the exclusive OR gate X₁ of the preceding cell in the second exclusive OR gate X₂ to provide a multiplication bit output stored in the register cᵢ. The output of the AND
The key element in an 8-bit and 10-bit switchable RS decoder is an 8-bit/10-bit programmable finite field multiplier in the syndrome computation block 10. This is due to the fact that finite field multipliers are the basic building blocks in implementing a RS decoder. A comparison of VLSI architectures of finite field multipliers using dual, normal or standard basis is discussed in I. S. Hsu, et al., "A Comparison of VLSI Architectures of Finite Field Multipliers Using, Dual, Normal or Standard Basis," IEEE Trans. on Computers, Vol. 37, 1988. Since any finite field element can be transformed into a standard basis representation irrespective of its original basis, the present invention focuses on the programmable design of a standard basis finite field multiplier.

FIG. 3 illustrates a logic diagram of a finite field multiplier described by P. A. Scott, et al., "A Fast Multiplier for GF(2^n)," IEEE Journal on Selected Areas in Communications, Vol. SAC-4, No. 1, January 1986. Based on this architecture, a mathematical theory is first developed for this finite field multiplier architecture as follows.
Assuming the two inputs of this multiplier are \( A = \alpha^i \) and \( B = \alpha^j \), respectively, where \( \alpha \) is the primitive element of \( GF(2^m) \), then both \( A \) and \( B \) can be represented as:

\[
A = \sum_{i=0}^{m-1} a_i \alpha^i, \quad \text{and} \quad B = \sum_{i=0}^{m-1} b_i \alpha^i
\]

The product of \( A \) and \( B \), i.e., \( C = \alpha^k \), can also be represented as:

\[
C = \sum_{i=0}^{m-1} c_i \alpha^i, \quad \text{where} \quad c_i = \sum_{r+s=i} a_r b_s
\]

By the use of Homer’s rule, the product \( C \) can be written as:

\[
C = AB = \sum_{i=0}^{m-1} (\sum_{r+s=i} a_r b_s) \alpha^i = (A_0 + A_1 \alpha + \ldots + A_{m-1} \alpha^{m-1}) (B_0 + B_1 \alpha + \ldots + B_{m-1} \alpha^{m-1}) \alpha^j = \sum_{i=0}^{m-1} c_i \alpha^i,
\]

where \( A_0, A_1, \ldots, A_{m-1} \) and \( B_0, B_1, \ldots, B_{m-1} \) are derived from the bit representation of \( A \) and \( B \) respectively, and \( c_i = \sum_{r+s=i} a_r b_s \) is the product of the two \( i \)-th terms.

FIG. 4 shows a logic diagram of a \((m+1)\)-bit finite field multiplier consisting of \( n+1 \) identical cells \( 0 \) to \( n \) with each cell containing three 1-bit registers \( f_i, c_i \), and \( a_i \), where \( i = 0, 1, 2, \ldots, n \). The cells are represented in the basis of \( \{ \alpha, \alpha^2, \ldots, \alpha^n \} \). Two AND gates \( G_1 \) and \( G_2 \) are used for the multiplication. When the signal \( ET \) is high, the feedback will be conducted from the last (tenth) cell and the highest two bits of the multiplicand \( A \), multiplier \( B \), and the polynomial \( f(X) \) are not set equal to zero. Setting \( b_0 \) and \( b_1 \) to zero for an 8-bit multiplication may be accomplished by an input gate \( ET-3 \) which received a timed control signal \( ET(9) \) during the 8th and 9th bit times of the serial multiplier \( B \) when the control signal \( ET \) is low to open the input line for the multiplier \( B \) during the 8th and 9th bit times of a multiplication cycle, or it can be controlled at the source of the multiplier \( B \).

**VLSI ARCHITECTURE OF A SINGLE-CHIP TYPE RS DECODER CHIP**

The development of this new architecture is based on the VLSI architecture of a RS decoder described in “A Comparison of VLSI Architectures for Time and Transform Domain Decoding of Reed-Solomon Codes,” by I. S. Hsu, et al., cited above. Because of the regularity of a time-domain RS decoder structure, the functional units in a RS decoder can be partitioned in an efficient manner. FIG. 6 shows the organization of a VLSI chip which is a basic building block of the single-chip type RS decoder system. The chip is partitioned into six functional sections. Section 30 contains all miscellaneous cells, eight syndrome computation subcells, 32 polynomial expansion subcells, 32 modified Euclidean subcells, and eight power expansion subcells. The programmability between 8-bit and 10-bit of an RS decoder is realized by making both the shift registers and the finite field multipliers in all the subcells programmable between 8-bit and 10-bit operation as discussed with reference to FIG. 5. In other words, each of the eight syndrome computation subcells is programmable by the signal \( ET \) for operation as either an 8-bit or 10-bit multiplier. The subcells of the remaining sections 32 through 36 are readily programmed for 8-bit or 10-bit operation by simply switching off the two most significant bit positions with the signal \( ET \) low.

The second section 32 in FIG. 6 has eight polynomial expansion subcells. The third section 33 consists of eight power expansion subcells. The fourth section 34 is composed of eight polynomial evaluation subcells which can also be used to do the “Chien Search” operation. The fifth section 35 has eight modified Euclidean subcells. Finally, the sixth section 36 of the VLSI chip contains all miscellaneous cells such as counters, shift registers, finite-field multipliers, and so forth. These miscellaneous cells are used as “glue” logic in a VLSI RS decoder system.

As shown in FIG. 7, if four of these VLSI chips shown in FIG. 6 are arrayed in tandem for operation as an 8-bit RS decoder, a (255, 223) time domain RS decoder is formed since there are enough subcells to implement all the functional units. In other words, there are 32 syndrome subcells, 32 power expansion subcells, 32 polynomial expansion subcells, 32 modified Euclid-
ean subcells and 32 polynomial evaluation and Chien search subcells. Since all the subcells are programmable between 8-bit and 10-bit, the core of a 10-bit (1023, 959) RS decoder is formed by arraying in tandem eight copies of the VLSI chip shown in FIG. 6. All that is necessary is control of the level of the signal ET.

It is estimated that the total number of pins required for a VLSI chip shown in FIG. 6 is less than 132 and the total number of transistors per chip is less than 60K. These requirements are well within the capability of today's VLSI technology.

The number of subcells in a VLSI chip could be reduced to half to decrease the silicon real estate and, therefore, increase chip yield by providing only 4 subcells in each functional section implemented on a VLSI chip. The number of transistors is then reduced from 60K, but the number of chips is doubled. On the other hand, if good fabrication technology is available, the number of functional subcells in a chip could be doubled such that the chip count in an RS decoder system is reduced by half. Therefore, this RS decoder architecture provides the maximum flexibility in both the chip and system designs.

CONFIGURATION OF A SINGLE-CHIP TYPE RS DECODER SYSTEM

The system configuration of the single-chip type RS decoder is shown in FIG. 8. The system is partitioned into 5 units 41 through 45. There is a host computer 41, which may be a personal computer, to issue commands to the whole system. An input module 42 which consists mostly of memory chips is used to store the received messages. Operations such as formatting, basis conversion if both standard or dual basis are used, zero-fill . . . , etc. will be performed in this unit. Similarly, an output module 43 is used to store the decoded symbols and performing operations such as basis reconversion, reformating, zero-stripping.

A control memory unit 44 is used to store all the control signals for controlling the VLSI chips. Due to the large number of control signals needed to control VLSI chips, it is not effective to include the control signal generation in the VLSI chips but rather in a separate dedicated chip. Moreover, partitioning of the VLSI chips will become very difficult if the control signal generators are included. It is expected that the control memory unit 44 will consist of EPROM's which store control signals of the VLSI chips. Further modifications or expansions of control signals for the VLSI chip will be relatively easy by this scheme. Finally, the fifth part 45 of the RS decoder system is the RS decoder VLSI chip set disclosed with reference to FIGS. 5, 6 and 7. This is the core of an RS decoder system which is switchable between 8-bit and 10-bit symbol sizes implemented with a single chip replicated many times and arrayed in tandem.

Although particular embodiments of the invention have been described and illustrated herein, it is recognized that modifications and variations may readily occur to those skilled in the art. Consequently, it is intended that the claims be interpreted to cover such modifications and variations.

We claim:

1. A standard-basis finite-field multiplier for a Reed-Solomon decoder that can correct both errors and erasures with a symbol size of n+1 bits comprised of n+1 cells, each cell consisting of three 1-bit registers fi, ci and ai, where i=0,1,2 . . . , n, two AND gates G1 and G2, and two exclusive OR gates X1 and X2, except the first cell which has only one exclusive OR gate X1, said 1-bit register ai being connected to receive a multiplicand bit represented in a basis of {a1, a2, a3} that is multiplied by an input multiplier B in serial form b3, b2, b1, b0, through said AND gate G1 and fed to the next cell i+1, and said exclusive OR gate X2 of cell i+1, except the last cell n which feeds back through said exclusive OR gate X1 directly to all cells through said AND gates G2 for multiplication with an irreducible primitive polynomial f(X) of the field in said 1-bit register fi, wherein the output of AND gate G2 of each cell except the first cell, where i=0, is combined with the output of the exclusive OR gate X1 of the preceding cell in the second exclusive OR gate X2 to provide a multiplicity bit output stored in the register ci and the output of the AND gate G3 of the first cell, where i=0, is stored directly in the register ci, and the output of each register ci of a cell is connected to one of two inputs of the first exclusive OR gate X1 of each cell, the other input to the exclusive OR gate X1 being from the gate G1 of the cell, whereby the outputs of the ci registers provide a parallel output product C1, C2, . . . , Cn.

2. A standard-basis finite-field multiplier as defined in claim 1 programmable between (n+1)-bit and (m+1)-bit symbol sizes, where m is an integer less than n, by a first electronic feedback switch connected between the output of the exclusive OR gate X1 of the last cell of cascaded cells m, . . . , 2, 1, 0 to an input of said AND gate G1 of each of the cells m, . . . , 2, 1, 0 under control of a binary program signal ET which commands an (m+1)-bit finite-field multiplier, and a second electronic feedback switch similarly connected between the output of the exclusive OR gate X1 of the last cell of cascaded cells n, . . . , m1, m2, m0 and an input of said AND gate G1 of each of said cells m, . . . , 2, 1, 0, said second switch being held cut off by the binary program signal ET, whereby upon switching said program signal to its alternate binary level, said first feedback switch is turned off and second feedback switch is turned on, thereby enabling said standard-basis finite-field multiplier to be programmably switched between (m+1)-bit and (n+1)-bit operation.

3. A standard-basis finite-field multiplier as defined in claim 2 wherein m=7 and n=9.

4. A basic single-chip building block for a RS decoder system partitioned into a plurality of sections the first of which consists of a plurality of syndrome subcells each of which contains identical standard-basis finite-field multipliers that are programmable between (m+1)-bit and (n+1)-bit symbol size operation, where m is an integer less than n, comprised of n+1 cells, each cell consisting of three 1-bit registers fi, ci and ai, where i=0, 1, 2 . . . , n, two AND gates G1 and G2, and two exclusive OR gates X1 and X2, except the first cell which has only one exclusive OR gate X1, said 1-bit register ai being connected to receive a multiplicand bit represented in a basis of {a1, a2, a3} that is multiplied by an input multiplier B in serial form b3, b2, b1, b0, through said AND gate G1 and fed to the next cell i+1, and said exclusive OR gate X2 of cell i+1, except the last cell n which feeds back through said exclusive OR gate X1 directly to all cells through said AND gates G2 for multiplication with an irreducible primitive polynomial f(X) of the field in said 1-bit register fi, wherein the output of AND gate G2 of each cell except the first cell,
where $i=0$, is combined with the output of the exclusive OR gate $X_1$ of the preceding cell in the second exclusive OR gate $X_2$ to provide a multiplication bit output stored in the register $c_i$ and the output of the AND gate $G_2$ of the first cell, where $i=0$, is stored directly in the register $c_0$ and the output of each register $c_i$ of a cell is connected to one of two inputs of the first exclusive OR gate $X_1$ of each cell, the other input to the exclusive OR gate $X_1$ being from the gate $G_1$ of the cell, whereby the outputs of the $c_i$ registers provide a parallel output product $C_n \ldots , C_2, C_1, C_0$, wherein said syndrome subcells are each programmable between $(n+1)$-bit and $(m+1)$-bit symbol size by a first electronic feedback switch connected between the output of the exclusive OR gate $X_1$ of the last cell of cascaded cells $m, \ldots, 2, 1, 0$ to an input of said AND gate $G_1$ of each of the cells $m, \ldots, 2, 1, 0$ under control of a binary program signal $ET$ which commands an $(m+1)$-bit finite-field multiplier, and a second electronic feedback switch similarly connected between the output of the exclusive OR gate $X_1$ of the last cell of cascaded cells $n, \ldots, m, \ldots, n_1, n_2, n_0$ and an input of said AND gate $G_1$ of each of said cells $m, \ldots, 2, 1, 0$, said second switch being held cut off by the binary program signal $ET$, whereby upon switching said program signal to its alternate binary level, said first feedback switch is turned off and second feedback switch is turned on, thereby enabling said standard-basis finite-field multiplier to be programmably switched between $(m+1)$-bit and $(n+1)$-bit operation, whereby a desired number of identical basic building blocks may be assembled to provide a RS decoder of any syndrome subcell size that is programmable between $(m+1)$-bit and $(n+1)$-bit operation.

5. A standard basis finite-field multiplier as defined in claim 4 wherein $m=7$ and $n=9$.