ELEC 6131: Error Detecting and Correcting Codes

Instructor:
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Time and Place: Tuesday, 17:45 – 20:15.
Office Hours: Tuesday, 15:00 – 17:00

LECTURE 7: Reed Solomon Codes

Reed Solomon (RS) Codes

- In the last lecture, we discussed binary BCH codes. Binary BCH codes can be generalized to non-binary codes. In a non-binary code, codewords consist of symbols which are each $m \geq 2$ bits long.
- In general, non-binary codes can be defined over any Galois Field GF(q) where q is either a prime or a power of a prime. However, for obvious reasons, people are most interested in codes defined over $GF(2^m)$.
- RS Codes are a sub-class of non-binary BCH Codes. For Reed-Solomon Codes, take some integer *m*. Then each symbol is *m* bits long. This means that symbols belong to $\{0,1,\dots,2^{m-1}\}$.
- An (*n*, *k*) RS code consists of *n* symbols each of which is *m* bits long and has *k* information symbols and *n*-*k* parity symbols.
- For an RS code over $GF(2^m)$ we have $n = 2^m - 1$.
- *k* can be any value less than *n*.
- An *(n, k)* RS code has the minimum distance $d_{min} = n - k + 1$.
- It can correct $t = \left\lfloor \frac{d_{min}-1}{2} \right\rfloor = \left\lfloor \frac{n-k}{2} \right\rfloor$

Reed Solomon (RS) Codes

- An (n, k) RS code over $GF(2^m)$ has codewords of length n symbols, i.e., $n * m$ bits out of which $k * m$ are information (or systematic) bits.
  - For example, a (255,239) RS Code over $GF(2^8)$ has codewords each 255 bytes and each codeword has 239 bytes of information and $(n\text{-}k)$ = 16 bytes of parity. Such a code can correct up to $\frac{16}{2} = 8$ bytes of error.
  - Note that here when we correct one symbol, we may have corrected $1,2, \ldots, m$ bits. If we have a burst of errors, that is a lot of errors adjacent to one another, RS Codes can be very useful. An RS Code which can correct t error symbols can correct $(t-1)m$ bits long bursts.
  - The generating polynomial of t error correcting RS Code is:

$$g(x) = (x + \alpha)(x + \alpha^2) \ldots (x + \alpha^{2t})$$

$$= g_0 + g_1 x + g_2 x^2 + \cdots + g_{2t-1} x^{2t-1} + x^{2t}$$

with $g_i \in GF(2^m)$ for $0 \le i \le 2t$.

  - $\alpha, \alpha^2, \ldots \alpha^{2t}$ are roots of $X^n + 1$, so $g(x)$ divides $X^n + 1$. So, $g(x)$ generates a $2^m - ry$ cyclic code of length n with $2t$ parity symbols.

Encoding of RS Codes

- We can simply multiply the information polynomial *u(x)* by *g(x)*. However, this may not result in a systematic code. To make the code systematic, we multiply *u(x)* by X^{n-k} to get X^{n-k}*u(x)* which we divide by *g(x)* to get:

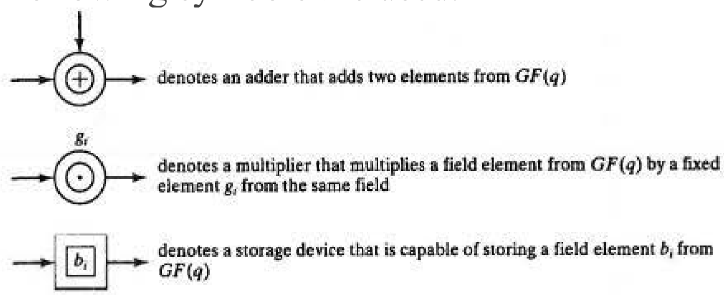
$$X^{n-k}u(x) = q(x)g(x) + b(x)$$

$q(x)g(x)$ is a code polynomial. So we have:

$$v(x) = q(x)g(x) = x^{n-k}u(x) + b(x)$$

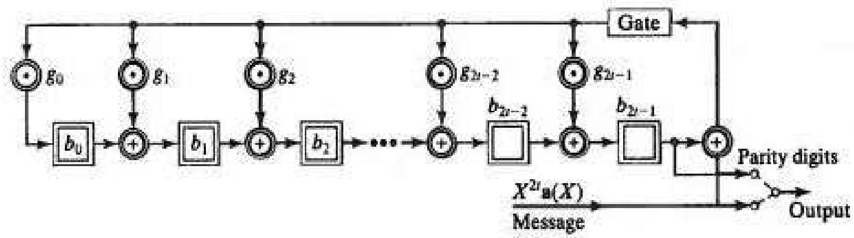
- This means that we have *u(x)* as part of *v(x)*, i.e., the code is systematic and *b(x)* is the parities polynomial.

The circuit on the next slide shows the encoding procedure. Too distinguish *m-ary* operation from binary, the following symbols are used.



Encoding of RS Codes

The following circuit shows the encoding procedure:



Encoding circuit for a q-ary RS code with generator polynomial $\mathbf{g}(X) = g_0 + g_1X + g_2X^2 + \cdots + g_{2t-1}X^{2t-1} + X^{2t}$.

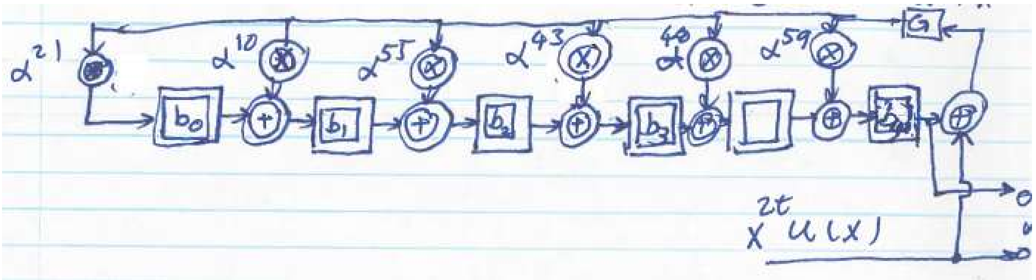
1) First, we close the gate and feed the information symbols into the division circuit. At the same time these information symbols are put on the line (to be transmitted): switch in lower position.
2) After feeding all *k* symbols, we open the gate (disconnect the feedback) and put switch in the up position, transmitting *2t* parity symbols.

Encoding of RS Codes: Example

- Find the generating polynomial of triple error correcting code over $GF(2^6)$.

$$g(x) = (x+\alpha)(x+\alpha^2)(x+\alpha^3)(x+\alpha^4)(x+\alpha^5)(x+\alpha^6)$$

$$=\alpha^{21} + \alpha^{10}x + \alpha^{55}x^2 + \alpha^{43}x^3 + \alpha^{48}x^4 + \alpha^{59}x^5 + x^6$$



- The Parity-Check matrix of an RS code is given as:

$$H = \begin{bmatrix} 1 & \alpha & \alpha^2 & \cdots & \alpha^{n-1} \\ 1 & \alpha^2 & (\alpha^2)^2 & \cdots & (\alpha^2)^{n-1} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & \alpha^{2t} & (\alpha^{2t})^2 & \cdots & (\alpha^{2t})^{n-1} \end{bmatrix}$$

Decoding of RS Codes

- **Decoding of RS Codes:**

1) Find syndrome.
2) Find error-locator polynomial.
3) Find error-value evaluator.
4) Find the error locations and error values and correct.

- Assume that the codeword $\underline{v} = (v_0, v_1, \dots, v_{n-1})$ is transmitted or equivalently

$$v(x) = v_0 + v_1 x + v_2 x^2 + \cdots + v_{n-1} x^{n-1}$$

- Assume that r(x) is received:

$$r(x) = r_0 + r_1 x + r_2 x^2 + \cdots + r_{n-1} x^{n-1}$$

Decoding of RS Codes

- $r(x) = v(x) + e(x)$, where $e(x)$ is the error polynomial

$$e(x) = r(x) + v(x) = e_0 + e_1 x + \cdots + e_{n-1} x^n$$

- Assume we have errors at locations: $j_1, j_2, \cdots, j_\gamma$
- Denote the values of error by $e_{j_1}, e_{j_2}, \dots, e_{j_\gamma}$, we have:

$$e_i = \begin{cases} 0 & i \neq j_1, \dots, j_\gamma \\ e_{j_e} \; if & i = j_e \epsilon \{j_1, \dots, j_e\} \end{cases}$$

- So, we can write:

$$e(x) = e_{j_1} x^{j_1} + e_{j_2} x^{j_2} + \cdots + e_{j_\gamma} x^{j_\gamma}$$

Decoding of RS Codes

- So, what we need to do is to find $j_1, \dots, j_\gamma$ as well as $e_{j_1}, \dots, e_{j_\gamma}$.
- That is, we have 2γ unknowns.
- Remember that

$$v(\alpha^i) = 0 \qquad i = 1,2, \dots, 2t$$
$$r(\alpha^i) = v(\alpha^i) + e(\alpha^i) = s_i$$

- So, $s_i = r(\alpha^i) = e(\alpha^i)$
- That is, we substitute $\alpha^i,\ i = 1,2, \dots, 2t$ in $r(x)$ to get *2t* syndromes. These provide *2t* equations with j_i's and e_{j_i}'s as their components. In order to be able to solve for the 2γ unknowns, we need to have 2γ equations, i.e., $2t = 2\gamma \rightarrow t = \gamma$. That is a proof that RS Code can correct *t* errors.

Decoding of RS Codes

- Now let's expand $s_i = e(\alpha^i)\,'\,s$:

$$s_1 = e_{j_1}\alpha^{j_1} + e_{j_2}\alpha^{j_2} + \cdots + e_{j_\gamma}\alpha^{j_\gamma}$$
$$s_2 = e_{j_1}\alpha^{2j_1} + e_{j_2}\alpha^{2j_2} + \cdots + e_{j_\gamma}\alpha^{2j_\gamma}$$
$$\vdots$$
$$s_{2t} = e_{j_1}\alpha^{2tj_1} + e_{j_2}\alpha^{2tj_2} + \cdots + e_{j_\gamma}\alpha^{2tj_\gamma}$$

- Let $\beta_i \triangleq \alpha^{j_i}$ and $\delta_i \triangleq e_{j_i}$, for $1 \le i \le \gamma$. Then:

$$s_1 = \delta_1\beta_1 + \delta_2\beta_2 + \cdots + \delta_\gamma\beta_\gamma$$
$$s_2 = \delta_1{\beta_1}^2 + \delta_2{\beta_2}^2 + \cdots + \delta_\gamma\beta_\gamma^2$$
$$\vdots$$
$$s_{2t} = \delta_1\beta_1^{2t} + \delta_2\beta_2^{2t} + \cdots + \delta_\gamma\beta_\gamma^{2t}$$

Decoding of RS Codes

- Define the error locator polynomial:

$$\sigma(x) = (1 + \beta_1 x)(1 + \beta_2 x) \dots (1 + \beta_\gamma x)$$
$$= \sigma_0 + \sigma_1 x + \sigma_2 x^2 + \cdots + \sigma_\gamma x^\gamma$$

- We can see that:

$$\sigma_0 = 1$$
$$\sigma_1 = \beta_1 + \beta_2 + \cdots + \beta_\gamma = s_1$$
$$\sigma_2 = \beta_1\beta_2 + \cdots + \beta_{\gamma-1}\beta_\gamma = \sigma_1 s_1 + s_2$$
$$\vdots$$

- Overall, we get the following equations named Newton equalities:

$$s_{\gamma+1} + \sigma_1 s_\gamma + \sigma_2 s_{\gamma-1} + \cdots + \sigma_\gamma s_1 = 0$$
$$s_{\gamma+2} + \sigma_1 s_{\gamma+1} + \sigma_2 s_\gamma + \cdots + \sigma_\gamma s_2 = 0$$
$$\vdots$$
$$s_{2t} + \sigma_1 s_{2t-1} + \sigma_2 s_{2t-2} + \cdots + \sigma_\gamma s_{2t-\gamma} = 0$$

See slide 27 for proof.

Decoding of RS Codes:

- The same as BCH Codes, we start from σ(x)=1 in stage 0 say we call it $\sigma^{(0)}(x)$ and try to increase the number of terms so that all equations are satisfied.
- Assume that at stage μ we have:

$$\sigma^{(\mu)}(x) = \sigma_0^{(\mu)} + \sigma_1^{(\mu)}x + \cdots + \sigma_{L_\mu}^{(\mu)}x^{l_\mu}$$

This means that we have coefficients $\sigma_0^{(\mu)}, \sigma_1^{(\mu)}, \ldots, \sigma_{L_\mu}^{(\mu)}$ of a polynomial that satisfies the first μ Newton equalities. We try to apply these coefficients to μ+1-st equality, i.e., form

$$S_{\mu+1} + \sigma_1^{(\mu)}S_\mu + \cdots + \sigma_{L_\mu}^{(\mu)}S_{\mu+1-l}$$

- If this gives us a zero it means that $\sigma_0^{(\mu)}, \sigma_1^{(\mu)}, \ldots + \sigma_{L_\mu}^{(\mu)}$ satisfy μ+1-st equality, otherwise we have to modify the polynomial.
- So, find the discrepancy:

$$d_\mu = S_{\mu+1} + \sigma_1^{(\mu)}S_\mu + \sigma_2^{(\mu)}S_{\mu-1} + \cdots + \sigma_{L\mu}^{(\mu)}S_{\mu+1-L}$$

Decoding of RS Codes:

- If the discrepancy $d_\mu = 0$ then:

$$\sigma^{(\mu+1)}(x) = \sigma^{(\mu)}(x)$$

and continue. Otherwise:

$$\sigma^{(\mu+1)}(x) = \sigma^{(\mu)}(x) + d_\mu d_\rho^{-1} x^{\mu-\rho} \sigma^{(\rho)}(x)$$

where ρ is the stage closest to μ such that $d_\rho \neq 0$ and $\rho - l_\rho$ has the largest value. Then:

$$l_\mu = \max(l_\mu, l_\rho + \mu - \rho)$$

- Continue this iteration until we get to stage *2t* then:

$$\sigma(x) = \sigma^{(2t)}(x)$$

- Initialization: start by filling out the first two rows:

Berlekamp's iterative procedure for finding the error-location polynomial of a q-ary BCH code.

μ	$\sigma^{(\mu)}(X)$	d_μ	l_μ	$\mu - l_\mu$
-1	1	1	0	-1
0	1	S_1	0	0
1	$1 - S_1 X$			
2				
3				
⋮				
$2t$				

Decoding of RS Codes: Example

- Consider triple-error correcting code over $GF(2^4)$. Let $r(x) = \alpha^7 x^3 + \alpha^3 x^6 + \alpha^4 x^{12}$
- Then:

$$g(x) = (x+\alpha)(x+\alpha^2)(x+\alpha^3)(x+\alpha^4)(x+\alpha^5)(x+\alpha^6)$$
$$= \alpha^6 + \alpha^9 x + \alpha^6 x^2 + \alpha^4 x^3 + \alpha^{14} x^4 + \alpha^{10} x^5 + x^6$$
$$s_1 = r(\alpha) = \alpha^{10} + \alpha^9 + \alpha = \alpha^{12}$$
$$s_2 = r(\alpha^2) = \alpha^{13} + 1 + \alpha^{13} = 1$$
$$s_3 = r(\alpha^3) = \alpha + \alpha^6 + \alpha^{10} = \alpha^{14}$$
$$s_4 = r(\alpha^4) = \alpha^4 + \alpha^{12} + \alpha^7 = \alpha^{10}$$
$$s_5 = r(\alpha^5) = \alpha^7 + \alpha^3 + \alpha^4 = 0$$
$$s_6 = r(\alpha^6) = \alpha^{10} + \alpha^9 + \alpha = \alpha^{12}$$

TABLE 7.2: Steps for finding the error-location polynomial of the (15,9) RS code over $GF(2^4)$.

μ	$\sigma^{(\mu)}(X)$	d_μ	l_μ	$\mu - l_\mu$
−1	1	1	0	−1
0	1	α^{12}	0	0
1	$1+\alpha^{12}X$	α^7	1	0(take $\rho = -1$)
2	$1+\alpha^3X$	1	1	1(take $\rho = 0$)
3	$1+\alpha^3X+\alpha^3X^2$	α^7	2	1(take $\rho = 0$)
4	$1+\alpha^4X+\alpha^{12}X^2$	α^{10}	2	2(take $\rho = 2$)
5	$1+\alpha^7X+\alpha^4X^2+\alpha^6X^3$	0	3	2(take $\rho = 3$)
6	$1+\alpha^7X+\alpha^4X^2+\alpha^6X^3$	—	—	—

Step 2. To find the error-location polynomial $\sigma(X)$, we fill out Table 7.1 and obtain Table 7.2. Thus, $\sigma(X) = 1 + \alpha^7 X + \alpha^4 X^2 + \alpha^6 X^3$.

Step 3. By substituting $1, \alpha, \alpha^2, \cdots, \alpha^{14}$ into $\sigma(X)$, we find that α^3, α^9, and α^{12} are roots of $\sigma(X)$. The reciprocals of these roots are α^{12}, α^6, and α^3, which are the error-location numbers of the error pattern $\mathbf{e}(X)$. Thus, errors occur at positions X^3, X^6, and X^{12}.

Decoding of RS Codes: Vicker's Formulation

- A more straightforward algorithm where the correction term is evolved as the iterations go ahead is given in Vicker's text. The algorithm is as follows:

1) Compute syndromes $S_1, \ldots, S_{2t}$.
2) Initialize the algorithm by letting μ=0, $\sigma^{(0)}(x) = 1, \;\; l = 0$ and $T(x) = x$
3) Set μ=μ+1 and compute discrepancy d_μ ,

$$d_\mu = S_\mu + \sum_{i=1}^{l} \sigma_i^{(\mu-1)} S_{\mu-i}$$

4) If $d_\mu = 0$ then go to 8.
5) Modify the polynomial as:

$$\sigma^{(\mu)}(x) = \sigma^{(\mu-1)}(x) + d_\mu T(x)$$

Decoding of RS Codes: Vicker's Formulation

6) If $2l \geq \mu$ then go to step 8.

7) Set $l = \mu - l$ and $T(x) = d_\mu^{-1}\sigma^{(\mu-1)}(x)$.

8) Set $T(x) = x.T(x)$.

9) If $\mu < 2t$ go to step 3.

10) Determine $\sigma(x) = \sigma^{(2t)}(x)$. If the roots are distinct and in the right field, then determine the error values, correct the errors and STOP.

11) Declare a decoding failure and STOP.

- In the next slide, we do the previous example again using Vicker's notation.

Decoding of RS Codes: Vicker's Formulation

- Form the table with the following syndromes:

$$s_1 = \alpha^{12}, s_2 = 1, s_3 = \alpha^{14}, s_5 = 0\ , s_6 = \alpha^{12}$$

This table shows the formation of error locator polynomial:

$$\sigma(x) = 1 + \alpha^7 x + \alpha^4 x^2 + \alpha^6 x^3$$

μ	s_μ	$\sigma^{(\mu)}(x)$	$d^{(\mu)}$	L_μ	T(x)
0	-	1	-	0	x
1	α^{12}	$1+\alpha^{12}x$	α^{12}	1	$\alpha^3 x$
*2	1	$1+\alpha^3 x$	α^7	1	$\alpha^8 x+\alpha^5 x^2$
**3	α^{14}	$1+\alpha^{13}x+\alpha^5 x^2$	1	2	$x+\alpha^3 x^2$
4	α^{10}	$1+\alpha^4 x+\alpha^{12}x^2$	α^{11}	2	$\alpha^4 x+\alpha^2 x^2+\alpha^9 x^3$
5	0	$1+\alpha^9 x+\alpha^4 x^3$	α^{10}	3	$\alpha^5 x+\alpha^9 x^2+\alpha^3 x^3$
6	α^{12}	$1+\alpha^7 x+\alpha^4 x^2 +\alpha^6 x^3$	α^{10}	3	-

$$* \ d_1 = s_2 + \sigma_1 s_1 = 1 + \alpha^{12}.\alpha^{12} = \alpha^9 + 1 = \alpha^7$$

$$** \ d_2 = s_3 + \sigma_1 s_2 = 1 + \alpha^{14} + \alpha^3.1 = 1$$

Decoding of RS Codes: Example

- Consider (7,3) RS Code over GF(8) with $r(x) = \alpha^2 x^6 + \alpha^2 x^4 + x^3 + \alpha^5 x^2$.
- Although we have done the generation of g(x) and encoding, let's start from ground zero for doing some exercise in Galois field arithmetic. Let's start with p(x)= x^3+x+1. Take α to be a primitive element of this field, i.e., ρ(x). That is $\alpha^3 + \alpha + 1 = 0$ or $\alpha^3 = \alpha+1$.

0	0	0	0	0
1	1	0	0	1
α^1	0	1	0	α
$\alpha^2 = \alpha.\alpha$	0	0	1	α^2
$\alpha^3 = \alpha^2.\alpha$	1	1	0	α+1
α^4	0	1	1	$\alpha^2 + \alpha$
α^5	1	1	1	$\alpha^2 + \alpha + 1$
α^6	1	0	1	$\alpha^2 + 1$
α^7	1	0	0	1

Note:

$\alpha^3 = \alpha^2.\alpha = \alpha + 1$

$\alpha^4 = \alpha.\alpha^3 = \alpha(\alpha + 1) = \alpha^2 + \alpha$

$\alpha^5 = \alpha^4.\alpha = (\alpha^2 + \alpha)\alpha = \alpha^3 + \alpha^2 = \alpha^2 + \alpha + 1$

$\alpha^6 = \alpha\,(\alpha^2 + \alpha + 1) = \alpha^2 + 1$

$\alpha^7 = \alpha\,(\alpha^2 + 1) = \alpha^3 + \alpha = \alpha + 1 + \alpha = 1$

Decoding of RS Codes: Example

- Now, $g(x)$ is:

$$g(x) = (x+\alpha)(x+\alpha^2)(x+\alpha^3)(x+\alpha^4)$$
$$= [x^2 + (\alpha+\alpha^2)x + \alpha^3][x^2 + (\alpha^3+\alpha^4)x + \alpha^7]$$
$$= [x^2 + \alpha^4 x + \alpha^3][x^2 + \alpha^6 x + 1]$$
$$= x^4 + \alpha^3 x^3 + x^2 + \alpha x + \alpha^3$$

- Computing Syndromes:

$$S_i = r(\alpha^i). \quad i = 1,2,3,4$$

- In this case, since the number of parities are less than the number of information symbols, it is reasonable to use $r(\alpha^i) = S_i$. However, for high rate codes where $n - k \ll k$, it is better to divide r(x) by g(x) to get

$$r(x) = g(x)\, q(x) + b(x)$$

Where $b(x)$ is a polynomial of degree less than or equal *n-k*.

$$S_i = r(\alpha^i) = g(\alpha^i)q(\alpha^i) + b(\alpha^i) \qquad i = 1,2,\dots,2t.$$

Since $g(\alpha^i) = 0 \qquad i = 1,\dots,2t,$

$$S_i = b(\alpha^i)$$

Decoding of RS Codes: Example

- Dividing $r(x) = \alpha^2 x^6 + \alpha^2 x^4 + x^3 + \alpha^5 x^2$ by $g(x)$

$$r(x) = (\alpha^2 x^2 + \alpha^5 x)g(x) + \alpha x^4 + \alpha^6 x^3 + \alpha^6 x^2 + \alpha x.$$

- So:

$$s_1 = b(\alpha) = \alpha^5 + \alpha^9 + \alpha^8 + \alpha^2 = \alpha^6$$
$$s_2 = b(\alpha^2) = \alpha^9 + \alpha^{12} + \alpha^{10} + \alpha^3 = \alpha^3$$
$$s_3 = b(\alpha^3) = \alpha^{13} + \alpha^{15} + \alpha^{12} + \alpha^4 = \alpha^4$$
$$s_4 = b(\alpha^4) = \alpha^{17} + \alpha^{18} + \alpha^{14} + \alpha^5 = \alpha^3$$

- Using Berlekamp's algorithm, we find $\sigma(x) = 1 + \alpha^2 x + \alpha x^2$

μ	S_μ	$\sigma^{(\mu)}(x)$	d_μ	L	$T(x)$
0	-	1	-	0	x
1	α^6	$1 + \alpha^6 x$	α^6	1	αx^*
2	α^3	$1 + \alpha^4 x$	α^2	1	$\alpha x^{2^{**}}$
3	α^4	$1 + \alpha^4 x + \alpha^6 x^2$	α^5	2	$\alpha^2 x + \alpha^6 x^2$
4	α^3	$1 + \alpha^2 x + \alpha x^2$	α^6	-	-

Decoding of RS Codes: Example

- Notes:
- For μ=1 L=0 $\rightarrow 2L < \mu \rightarrow L = \mu - L = 1$ and

$$T(x) = \frac{\sigma^{(0)}(x)}{d_1} = \frac{x}{\alpha^6} = \alpha x.$$

- For μ=2

$$d_\mu = s_\mu + \sum_{i=1}^{L} \sigma_i{}^{(\mu-1)} s_{\mu-i} \rightarrow \mu_2 = s_2 + \sigma_1^{(1)} S_1$$

Or

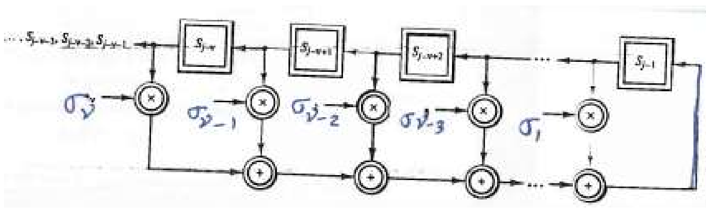
$$\mu_2 = \alpha^3 + \alpha^6 . \alpha^6 = \alpha^3 + \alpha^5 = \alpha^2$$
$$2L = 2 \geq \mu = 2 \rightarrow T(x) = xT(x) \rightarrow T(x) = \alpha x^2$$

Decoding of RS Codes

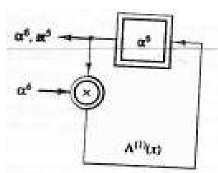
- The Massy Algorithm is based on Linear Feedback Shift Register (LFSR) synthesis technique.
- Note that for γ errors, we have the following Newton equalities.

$$s_j = \sigma_1 s_{j-1} + \sigma_2 s_{j-2} + \cdots + \sigma_\gamma s_{j-\gamma}$$

- This relationship can be represented as LFSR circuit looking like:

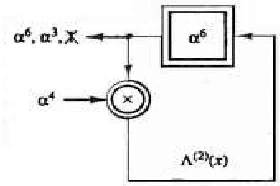


- The problem of finding error-locator polynomial is then to find an LFSR of minimal length such that the first 2t elements in the output sequence are $s_1, s_2, \ldots, s_{2t}$.
- The coefficients of the filter are then the coefficient of σ(x).
- For the above (7,3) RS code, we start with:

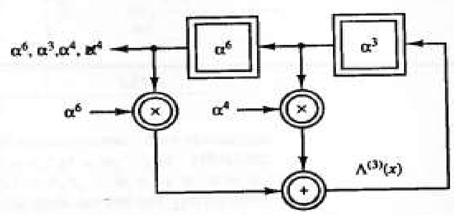


Decoding of RS Codes

- This works for the $s_1 = \alpha^6$ as it outputs the content of the register ,i.e., α^6. But after the application of the seconds clock, the output will be $\alpha^6.\alpha^6 = \alpha^{12} = \alpha^5$ which is not $s_{2=}\alpha^3$.
- To correct the situation, we change the filter tap to α^4 which is $\frac{\alpha^6}{\alpha^2}$ and therefore, the output after the clocking will be $\frac{\alpha^5}{\alpha^2} = \alpha^3 = s_2$.

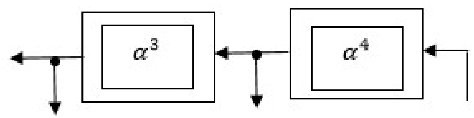


- After the next clock the output will be $\alpha^3.\alpha^4 = 1$ which is not equal to $s_3 = \alpha^4$.
- To correct this we need to add α^5 so that, we get $1 + \alpha^5 = \alpha^4 = s_3$. We keep the above and add a stage with α^6 in the register and α^6 as the tap.

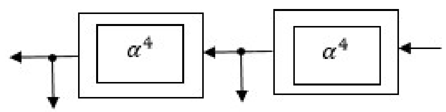


Decoding of RS Codes

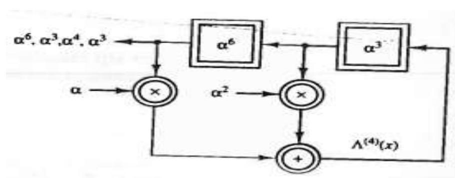
- This circuit outputs α^6 first and then calculates $\alpha^6.\alpha^6 + \alpha^3.\alpha^4 = \alpha^5 + 1 = \alpha^4$
- Content of the rightmost SR is moved to left and α^4 is loaded into it.



- So, the next output is $\alpha^3 = s_2$.
- Next $\alpha^3.\alpha^6 + \alpha^4.\alpha^4 = \alpha^2 + \alpha = \alpha^4$ is placed in right register and α^4 is moved left:



- Now α^4 is output which is s_3. But the next output is $\alpha^4 \neq s_4 = \alpha^3$
- To correct this, we modify the taps of the LFSR to:



- It is easy to see that this circuit outputs $\alpha^6, \alpha^3, \alpha^4, \alpha^3, i.e.\ s_1, s_2, s_3, s_4$

Decoding of RS Codes: Finding Error Values

- We have found the error-locator polynomial σ(X). We can solve it, using Chien Search, to find the error locations $\beta_i = \alpha^{j_i}$ i=1,2, …,γ.
- Now we need to find $\delta_i = e_{j_i}$, i.e., error values at the error locations and correct them, That is the equations are:

$$S_1 = e_{j_1}\alpha^{j_1} + e_{j_2}\alpha^{j_2} + \cdots + e_{j_\gamma}\alpha^{j_\gamma}$$

$$\vdots$$

$$S_{2t} = e_{j_1}\alpha^{2tj_1} + e_{j_2}\alpha^{2tj_2} + \cdots + e_{j_\gamma}\alpha^{2tj_\gamma}$$

With $\alpha^{j_i}{}'s$ and S_i's known. Or equivalently:

$$S_1 = \delta_1\beta_1 + \delta_2\beta_2 + \cdots + \delta_\gamma\beta_\gamma$$

$$S_2 = \delta_1\beta_1^2 + \delta_2\beta_2^2 + \cdots + \delta_\gamma\beta_\gamma^2$$

$$\vdots$$

$$S_{2t} = \delta_1\beta_1^{2t} + \delta_2\beta_2^{2t} + \cdots + \delta_\gamma\beta_\gamma^{2t}$$

Decoding of RS Codes: Finding Error Values

- Let's define the syndrome polynomial:

$$S(x) = S_1 + S_2X + \cdots + S_{2t}X^{2t} + S_{2t+1}X^{2t} + \cdots$$
$$= \sum_{j=1}^{\infty} S_j X^{j-1}$$

- Note that $S(x)$ has an infinite number of terms whose first *2t* terms are known:

$$S_j = \sum_{l=1}^{\gamma} \delta_l \, \beta_l^j \qquad j = 1,2, \dots, 2t$$

- Substituting these (but now for all terms), we get:

$$S(x) = \sum_{j=1}^{\infty} x^{j-1} \sum_{l=1}^{\gamma} \delta_l \, \beta_l^j$$
$$= \textstyle\sum_{l=1}^{\gamma} \delta_l \, \beta_l \sum_{j=1}^{\infty} (\beta_l x)^{j-1}$$

- But

$$\sum_{j=1}^{\infty} (\beta_l x)^{j-1} = \frac{1}{1 + \beta_l x}$$

Decoding of RS Codes: Finding Error Values

- Substituting $\sum_{j=1}^{\infty}(\beta_l x)^{j-1} = \frac{1}{1+\beta_l x}$, we get:

$$S(x) = \sum_{l=1}^{\gamma} \frac{\delta_l \beta_l}{1 + \beta_l x}$$

- Multiplying $\sigma(x) = \prod_{i=1}^{\gamma}(1 + \beta_i x)$ and $S(x)$, we get:

$$S(x)\sigma(x) = \sum_{l=1}^{\gamma} \delta_l \, \beta_l \prod_{i=1.\, i \neq l}^{\gamma} (1 + \beta_i x) \triangleq Z_0(x)$$

- We can also write:

$$\begin{aligned} \sigma(x)S(x) &= \left[1 + \sigma_1 x + \cdots + \sigma_\gamma x^\gamma\right][S_1 + S_2 x + S_3 x^2 + \cdots] \\ &= S_1 + (S_2 + \sigma_1 S_1)x + (S_3 + \sigma_1 S_2 + \sigma_2 S_1)x^2 + \cdots \\ &\quad \ldots + \left(\sigma_{2t} + \sigma_1 S_{2t-1} + \cdots + \sigma_\gamma S_{2t-\gamma}\right)x^{2t-1} + \cdots \end{aligned}$$

- So:

$$\begin{aligned} Z_0(x) = S_1 + (S_2 + \sigma_1 S_1)x + (S_3 + \sigma_1 S_2 + \sigma_2 S_1)x^2 + \cdots \\ + (S_\gamma + \sigma_1 S_{\gamma-1} + \cdots + \sigma_{\gamma-1} S_1)x^{\gamma-1} \end{aligned}$$

Decoding of RS Codes: Finding Error Values

- Let's substitute β_k^{-1} in $Z_0(x)$:

$$Z_0(\beta_k^{-1}) = \sum_{l=1}^{\gamma} \delta_l \beta_l \prod_{i=1, i\neq l}^{\gamma} (1 + \beta_i \beta_k^{-1})$$

$$= \delta_k \beta_k \prod_{i=1, i\neq k}^{\gamma} (1 + \beta_i \beta_k^{-1})$$

- Taking derivative of σ(x):

$$\sigma'(x) = \frac{d}{dx} \prod_{i=1}^{\gamma} (1 + \beta_i x) = \sum_{l=1}^{\gamma} \beta_l \prod_{i=1, i\neq l}^{\gamma} (1 + \beta_i x)$$

Then

$$\sigma'(\beta_k^{-1}) = \beta_k \prod_{i=1, i\neq k}^{\gamma} (1 + \beta_i \beta_k^{-1})$$

- So,

$$\delta_k = \frac{Z_0(\beta_k^{-1})}{\sigma'(\beta_k^{-1})}$$

Decoding of RS Codes: Finding Error Values

- Let's $[\sigma(x)S(x)]_{2t}$ represent the first $2t$ terms of $\sigma(x)S(x)$. Then

$$\sigma(x)S(x) - [\sigma(x)S(x)]_{2t}$$

is divisible by X^{2t}.

- That is:

$$\sigma(x)S(x) \equiv [\sigma(x)S(x)]_{2t} mod\ X^{2t}$$

- But,

$$[\sigma(x)S(x)]_{2t} = Z_0(x)$$

and we have:

$$\sigma(x)S(x) \equiv Z_0(x) mod x^{2t}$$

- This is called the key equation that has to be solved in decoding of RS codes.

Decoding of RS Codes: Example

- Consider the (7, 3) code in the previous example:
- We had $S_1 = \alpha^6, S_2 = \alpha^3, S_3 = \alpha^4$ *and* $S_4 = \alpha^3$,
- So:

$$S(x) = \alpha^6 + \alpha^3 x + \alpha^4 x^2 + \alpha^3 x^3$$

- We also found:

$$\sigma(x) = 1 + \alpha^2 x + \alpha x^2 \rightarrow \sigma'(x) = \alpha^2 + 2\alpha x = \alpha^2$$

- So:

$$Z_0(x) = \sigma(x) S(x) mod x^4 = (1 + \alpha^2 x + \alpha x^2)(\alpha^6 + \alpha^3 x + \alpha^4 x^2 + \alpha^3 x^3)$$
$$= \alpha^6 + x$$

- We can find the error locations by solving σ(x)=0 to get $\beta_1 = \alpha^3$ and $\beta_2 = \alpha^5$
- So,

$$e_3 = \delta_1 = \frac{Z_0(\alpha^{-3})}{\sigma'(\alpha^{-3})} = \frac{\alpha^6 + (\alpha^{-3})}{\alpha^2} = \alpha^4 + \alpha^2 = \alpha$$

and

$$e_5 = \delta_2 = \frac{z_0(\alpha^{-5})}{\sigma'(\alpha^{-5})} = \frac{\alpha^6 + \alpha^{-5}}{\alpha^2} = \alpha^4 + 1 = \alpha^5$$

- So,

$$e(X) = \alpha X^3 + \alpha^5 X^5$$

Decoding of RS Codes: Another Example

- Consider the (15, 9) code we considered before.
- The syndromes are: $s_1 = \alpha^{12}$, $s_2 = 1$, $s_3 = \alpha^{14}$, $s_4 = \alpha^{10}$, $s_5 = 0$ and $s_6 = \alpha^{12}$
- We found that $\sigma(x) = 1 + \alpha^7 x + \alpha^4 x^2 + \alpha^6 x^3$.
- Letting $x = \alpha^3$, we get $\sigma(\alpha^3) = 0$. So, the roots of $\sigma(x)$ are α^3, α^6 and α^{12}.
- Therefore, errors are at locations x^3, x^6 and x^{12}.
- Now, we form the error-value evaluator function:

$$Z_0(x) = s_1 + (s_2 + \sigma_1 s_1)x + (s_3 + \sigma_1 s_2 + \sigma_2 s_1)x^2$$
$$=\alpha^{12} + (1 + \alpha^7\alpha^{12})x + (\alpha^{14} + \alpha^7 + \alpha^4\alpha^{12})x^2$$
$$= \alpha^{12} + (1 + \alpha^4)x + (\alpha^{14} + \alpha^7 + \alpha)x^2 = \alpha^{12} + \alpha x$$

- The error values are

$$e_3 = \frac{Z_0(\alpha^{-3})}{\sigma'(\alpha^{-3})} = \frac{\alpha^{12} + \alpha\alpha^{-3}}{\alpha^3(1 + \alpha^6\alpha^{-3})(1 + \alpha^{12}\alpha^{-3})} = \frac{\alpha}{\alpha^9} = \alpha^7$$
$$e_6 = \frac{Z_0(\alpha^{-6})}{\sigma'(\alpha^{-6})} = \frac{\alpha^{12} + \alpha\alpha^{-6}}{\alpha^6(1 + \alpha^3\alpha^{-6})(1 + \alpha^{12}\alpha^{-6})} = \frac{\alpha^3}{1} = \alpha^3$$
$$e_{12} = \frac{Z_0(\alpha^{-1}\ )}{\sigma'(\alpha^{-12})} = \frac{\alpha^{12} + \alpha\alpha^{-12}}{\alpha^{12}(1 + \alpha^3\alpha^{-12})(1 + \alpha^6\alpha^{-12})} = \frac{\alpha^6}{\alpha^2} = \alpha^4$$

So, the error pattern is:

$$e(x) = \alpha^7 x^3 + \alpha^3 x^6 + \alpha^4 x^{12}$$