

Information Theory

Chapter IV: Error control coding

What is error control coding?

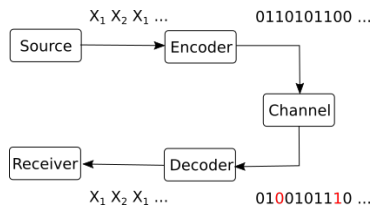


Figure 1: Communication system

- ▶ The second main task of coding: error control
- ▶ Protect information against channel errors

Mutual information and error control

- ▶ Mutual information $I(X, Y)$ = the information transmitted on the channel
- ▶ Why do we still need error control?
- ▶ Example: consider the following BSC channel ($p = 0.01$, $p(x_1) = 0.5$, $p(x_2) = 0.5$):

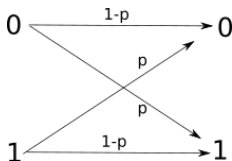


Figure 2: Binary symmetric channel (BSC)

- ▶ The receiver would like to know the source messages
 - ▶ In absence of communication, the uncertainty is $H(X) = 1$ bit/msg
 - ▶ With communication, the uncertainty is $H(X|Y) \approx 0.081$ bit/msg

Mutual information and error control

- ▶ The reduction in uncertainty due to communication = mutual information
 - ▶ $I(X, Y) = H(X) - H(X|Y) \approx 0.919$ bit/msg
- ▶ Even though we have large $I(X, Y)$, we still lose some information
 - ▶ Imagine downloading a file, but having 1% wrong bits

Why is error control needed?

- ▶ In most communications it is required that *all* bits are received correctly
 - ▶ Not 1% errors, not 0.1%, not 0.0001%. **None!**
- ▶ But that is not possible unless the channel is ideal.
- ▶ So what do to? **Error control coding**

Modelling the errors on the channel

- ▶ We consider only binary channels (symbols = $\{0, 1\}$)
- ▶ An error = a bit is changed from 0 to 1 or viceversa
- ▶ Errors can appear:
 - ▶ **independently**: each bit on its own
 - ▶ in **packets of errors**: groups of errors

Modelling the errors on the channel

- ▶ Changing the value of a bit = modulo-2 sum with 1
- ▶ Value of a bit remains the same = modulo-2 sum with 0

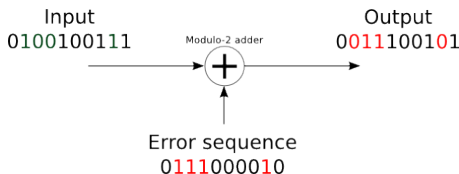


Figure 3: Channel error model

- ▶ Channel model we use (simple):
 - ▶ The transmitted sequence is summed modulo-2 with an **error sequence**
 - ▶ Where the error sequence is 1, there is a bit error
 - ▶ Where the error sequence is 0, there is no error

$$\mathbf{r} = \mathbf{c} \oplus \mathbf{e}$$

Mathematical properties of modulo-2 arithmetic

- ▶ Product is the same as for normal arithmetic
- ▶ Multiplication is distributive just like in normal case

$$a(b \oplus c) = ab \oplus ac$$

- ▶ Subtraction = addition. There is no negation. Each number is its own negative

$$a \oplus a = 0$$

Error detection vs correction

What can we do about errors?

- ▶ **Error detection:** find out if there is any error in the received sequence
 - ▶ don't know exactly where, so cannot correct the bits, but can discard whole sequence
 - ▶ perhaps ask the sender to retransmit (examples: TCP/IP, internet communication etc)
 - ▶ easier to do
- ▶ **Error correction:** find out exactly which bits have errors, if any
 - ▶ locating the error = correcting error (for binary channels)
 - ▶ can correct all errored bits by inverting them
 - ▶ useful when can't retransmit (data is stored: on HDD, AudioCD etc.)
 - ▶ harder to do than mere detection

Overview of error control coding process

The process of error control:

1. Want to send a sequence of k bits = **information word**

$$\mathbf{i} = i_1 i_2 \dots i_k$$

2. For each possible information word, the coder assigns a **codeword** of length $n > k$:

$$\mathbf{c} = c_1 c_2 \dots c_n$$

3. The codeword is sent on the channel instead of the original information word
4. The receiver receives a sequence $\hat{\mathbf{c}} \approx \mathbf{c}$, with possible errors:

$$\hat{\mathbf{c}} = \hat{c}_1 \hat{c}_2 \dots \hat{c}_n$$

5. The decoding algorithm detects/corrects the errors in $\hat{\mathbf{c}}$

Definitions

- ▶ An **error correcting code** is an association between the set of all possible information words to a set of codewords
 - ▶ Each possible information word \mathbf{i} has a certain codeword \mathbf{c}
- ▶ The association can be done:
 - ▶ randomly: codewords are selected and associated randomly to the information words
 - ▶ based on a certain rule: the codeword is computed with some algorithm from the information word
- ▶ A code is a **block code** if it operates with words of *fixed size*
 - ▶ Size of information word $\mathbf{i} = k$, size of codeword $\mathbf{c} = n$, $n > k$
 - ▶ Otherwise it is a *non-block code*
- ▶ A code is **linear** if any linear combination of codewords is also a codeword
- ▶ The **coding rate** of a code is:

$$R = k/n$$

Definitions

- ▶ A code C is an t -**error-detecting** code if it is able to *detect* t or less errors
- ▶ A code C is an t -**error-correcting** code if it is able to *correct* t or less errors
- ▶ Examples: at blackboard

A first example: parity bit

- ▶ Add parity bit to a 8-bit long information word, before sending on a channel
 - ▶ coding rate $R = 8/9$
 - ▶ can detect 1 error in a 9-bit codeword
 - ▶ detection algorithm: check if parity bit matches data
 - ▶ fails for 2 errors
 - ▶ cannot correct error (don't know where it is located)
- ▶ Add more parity bits to be able to locate the error
 - ▶ Example at blackboard
 - ▶ coding rate $R = 8/12$
 - ▶ can detect and correct 1 error in a 9-bit codeword

A second example: repetition code

- ▶ Repeat same block of data n times
 - ▶ want to send a k -bit information word
 - ▶ codeword to send = the information word repeated $n = 5$ times
 - ▶ coding rate $R = k/n = 1/5$
 - ▶ can detect and correct 2 errors, and maybe even more if they do not affect the same bit
 - ▶ error correcting algorithm = majority rule
 - ▶ not very efficient

Redundancy

- ▶ Because $k < n$, we introduce **redundancy**
 - ▶ to transmit k bits of information we actually send more bits (n)
- ▶ Error control coding adds redundancy, while source coding aims to reduce redundancy \rightarrow Contradiction?
 - ▶ but now redundancy is added in a controlled way, with a purpose
- ▶ Source coding and error control coding in practice: do sequentially, independently
 1. First perform source coding, eliminating redundancy in representation of data
 2. Then perform error control coding, adding redundancy for protection

Shannon's noisy channel theorem (second theorem, channel coding theorem)

- ▶ A coding rate is called **achievable** for a channel if, for that rate, there exists a coding and decoding algorithm guaranteed to correct all possible errors on the channel

Shannon's noisy channel coding theorem (second theorem)

For a given channel, all rates below capacity $R < C$ are achievable. All rates above capacity, $R > C$, are not achievable.

Channel coding theorem explained

In layman terms:

- ▶ For all coding rates $R < C$, **there is a way** to recover the transmitted data perfectly (decoding algorithm will detect and correct all errors)
- ▶ For all coding rates $R > C$, **there is no way** to recover the transmitted data perfectly

Example:

- ▶ Send binary digits on a BSC channel with capacity 0.7 bits/message
- ▶ For any coding rate $R < 0.7$ there exist an error correction code that allow perfect recovery
 - ▶ $R < 0.7$ = for every 7 bits of data, coding adds more than 3 bits, on average
- ▶ With less than 3 bits for every 7 bits of data \Rightarrow impossible to recover all data

Ideas behind channel coding theorem

- ▶ The rigorous proof of the theorem is too complex to present
- ▶ Key ideas of the proof:
 - ▶ Use very long information words, $k \rightarrow \infty$
 - ▶ Use random codes, compute the probability of having error after decoding
 - ▶ If $R < C$, *in average for all possible codes*, the probability of error after decoding goes to 0
 - ▶ If the average for all codes goes to 0, there exists at least one code better than the average
 - ▶ That is the code we should use
- ▶ **The theorem does not tell what code to use**, only that some code exists
 - ▶ There is no clue of how to actually find the code in practice
 - ▶ Only some general principles:
 - ▶ using longer information words is better
 - ▶ random codewords are generally good
- ▶ In practice, cannot use infinitely long codewords, so will only get a *good enough* code

Distance between codewords

Practical ideas for error correcting codes:

- ▶ If a codeword \mathbf{c}_1 is received with errors and becomes identical to another codeword $\mathbf{c}_2 \implies$ cannot detect any errors
 - ▶ Receiver will think it received a correct codeword c_2 and the information word was \mathbf{i}_2 , but actually it was \mathbf{i}_1
- ▶ We want codewords as different as possible from each other
- ▶ How to measure this difference? **Hamming distance**

Hamming distance

- ▶ The **Hamming distance** of two binary sequences **a**, **b** of length $n =$ the total number of bit differences between them

$$d_H(\mathbf{a}, \mathbf{b}) = \sum_{i=1}^N a_i \oplus b_i$$

- ▶ We need at least $d_H(a, b)$ bit changes to convert one sequence into another
- ▶ It satisfies the 3 properties of a metric function:
 1. $d_H(\mathbf{a}, \mathbf{b}) \geq 0 \quad \forall \mathbf{a}, \mathbf{b}$, with $d_H(\mathbf{a}, \mathbf{b}) = 0 \Leftrightarrow \mathbf{a} = \mathbf{b}$
 2. $d_H(\mathbf{a}, \mathbf{b}) = d_H(\mathbf{b}, \mathbf{a}), \forall \mathbf{a}, \mathbf{b}$
 3. $d_H(\mathbf{a}, \mathbf{c}) \leq d_H(\mathbf{a}, \mathbf{b}) + d_H(\mathbf{b}, \mathbf{c}), \forall \mathbf{a}, \mathbf{b}, \mathbf{c}$
- ▶ The **minimum Hamming distance of a code**, d_{Hmin} = the minimum Hamming distance between any two codewords **c**₁ and **c**₂
- ▶ Example at blackboard

Nearest-neighbor decoding

Coding:

- ▶ Design a code with large d_{Hmin}
- ▶ Send a codeword \mathbf{c} of the code

Decoding:

- ▶ Receive a word \mathbf{r} , that may have errors
- ▶ Error detecting:
 - ▶ check if r is part of the codewords of the code C :
 - ▶ if r is part of the code, decide that there have been no errors
 - ▶ if r is not a codeword, decide that there have been errors
- ▶ Error correcting:
 - ▶ if \mathbf{r} is a codeword, decide there are no errors
 - ▶ else, choose codeword **nearest** to the received \mathbf{r} , in terms of Hamming distance
 - ▶ this is known as **nearest-neighbor decoding**

Performance of nearest neighbor decoding

Theorem:

- ▶ If the minimum Hamming distance of a code is d_{Hmin} , then:
 1. the code can *detect* up to $d_{Hmin} - 1$ errors
 2. the code can *correct* up to $\left\lfloor \frac{d_{Hmin}-1}{2} \right\rfloor$ errors using nearest-neighbor decoding

Consequence:

- ▶ It is good to have d_{Hmin} as large as possible
 - ▶ This implies longer codewords, i.e. smaller coding rate, i.e. more redundancy

Performance of nearest neighbor decoding

Proof:

1. at least d_{Hmin} binary changes are needed to change one codeword into another, $d_{Hmin} - 1$ is not enough \Rightarrow the errors are detected
2. the received word \mathbf{r} is closer to the original codeword than to any other codeword \Rightarrow nearest-neighbor algorithm will find the correct one
 - ▶ because $\left\lfloor \frac{d_{Hmin}-1}{2} \right\rfloor =$ less than half the distance to another codeword

Note: if the number of errors is higher, can fail:

- ▶ Detection failure: decide that there were no errors, even if they were (more than $d_{Hmin} - 1$)
- ▶ Correction failure: choose a wrong codeword

Example: blackboard

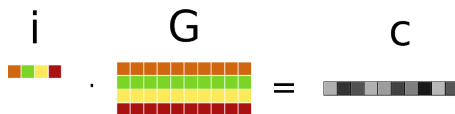
Linear block codes

- ▶ A code is a **block code** if it operates with words of *fixed size*
 - ▶ Size of information word $\mathbf{i} = k$, size of codeword $\mathbf{c} = n$, $n > k$
 - ▶ Otherwise it is a *non-block code*
- ▶ A code is **linear** if any linear combination of codewords is also a codeword
- ▶ A code is called **systematic** if the codeword contains all the information bits explicitly, unaltered
 - ▶ coding merely adds supplementary bits besides the information bits
 - ▶ codeword has two parts: the information bits and the parity bits
 - ▶ example: parity bit added after the information bits
- ▶ Otherwise the code is called **non-systematic**
 - ▶ the information bits are not explicitly visible in the codeword
- ▶ Example: at blackboard

Generator matrix

- ▶ All codewords for a linear block code can be generated via a **matrix multiplication**:

$$\mathbf{i} \cdot [\mathbf{G}] = \mathbf{c}$$



The diagram shows the matrix multiplication $\mathbf{i} \cdot [\mathbf{G}] = \mathbf{c}$. The vector \mathbf{i} is a 1x4 grid of colored squares (orange, green, yellow, red). The matrix \mathbf{G} is a 4x10 grid of colored squares (rows of orange, green, yellow, red). The resulting codeword \mathbf{c} is a 1x10 grid of gray squares.

Figure 4: Codeword construction with generator matrix

- ▶ $[\mathbf{G}] = \mathbf{generator\ matrix}$ of size $k \times n$
- ▶ Row-wise interpretation:
 - ▶ \mathbf{c} = a linear combination of rows in $[\mathbf{G}]$
 - ▶ The rows of $[\mathbf{G}]$ = a *basis* for the linear code
- ▶ All operations are done in modulo-2 arithmetic

Parity check matrix

- ▶ Every generator matrix $[G]$ has a complementary **parity-check matrix** $[H]$ such that

$$0 = [H] \cdot [G]^T$$

- ▶ How to check if a binary word is a codeword or not?
- ▶ For every codeword \mathbf{c} generated with $[G]$:

$$\boxed{0 = [H] \cdot \mathbf{c}^T}$$

- ▶ Proof:

$$\mathbf{i} \cdot [G] = \mathbf{c}$$

$$[G]^T \cdot \mathbf{i}^T = \mathbf{c}^T$$

$$[H] \cdot \mathbf{c}^T = [H] \cdot [G]^T \cdot \mathbf{i}^T = 0$$

Parity check matrix

- ▶ $[H]$ is the **parity-check matrix**, size = $(n - k) \times n$
- ▶ $[G]$ and $[H]$ are related, one can be deduced from the other
- ▶ The resulting vector $z = [H] \cdot [c]^T$ is the **syndrome**
- ▶ All codewords generated with $[G]$ will produce 0 when multiplied with $[H]$
- ▶ All binary sequences that are not codewords will produce $\neq 0$ when multiplied with $[H]$
- ▶ Column-wise interpretation of multiplication:

$$\begin{array}{c} z \\ \begin{array}{|c|c|c|c|c|c|c|c|c|c|} \hline \square \\ \square \\ \square \\ \square \\ \square \\ \square \\ \square \\ \square \\ \hline \end{array} \end{array} = \begin{array}{c} H \\ \begin{array}{|c|c|c|c|c|c|c|c|c|c|} \hline \text{colored grid} \\ \hline \end{array} \end{array} \cdot \begin{array}{c} r \\ \begin{array}{|c|} \hline \text{colored vector} \\ \hline \end{array} \end{array}$$

Figure 5: Codeword checking with parity-check matrix

[G] and [H] for systematic codes

- ▶ For systematic codes, [G] and [H] have special forms
- ▶ Generator matrix
 - ▶ first part = identity matrix
 - ▶ second part = some matrix Q

$$[G]_{k \times n} = [Q_{k \times (n-k)} \quad I_{k \times k}]$$

- ▶ Parity-check matrix
 - ▶ first part = identity matrix
 - ▶ second part = same Q , transposed

$$[H]_{(n-k) \times n} = [I_{(n-k) \times (n-k)} \quad Q_{(n-k) \times k}^T]$$

- ▶ Can easily compute one from the other
- ▶ Example at blackboard

Interpretation as parity bits

- ▶ The additional bits added by coding are actually just parity bits
 - ▶ Proof: write the generation equations (example)
- ▶ Generator matrix $[G]$ creates the codeword as:
 - ▶ first part = information bits (systematic code, first part of $[G]$ is identity matrix)
 - ▶ additional bits = combinations of information bits = *parity bits*
- ▶ Parity-check matrix $[H]$ checks if parity bits correspond to information bits
 - ▶ Proof: write down the parity check equation (see example)
- ▶ If all parity bits match the data, the syndrome $\mathbf{z} = 0$
 - ▶ otherwise the syndrome $\mathbf{z} \neq 0$
- ▶ **Generator & parity-check matrices are just mathematical tools for easy computation & checking of parity bits**

Syndrome-based error detection

Syndrome-based error **detection** for linear block codes:

1. generate codewords with generator matrix:

$$\mathbf{i} \cdot [\mathbf{G}] = \mathbf{c}$$

2. send codeword \mathbf{c} on the channel
3. a random error word \mathbf{e} is applied on the channel
4. receive word $\mathbf{r} = \mathbf{c} \oplus \mathbf{e}$
5. compute **syndrome** of \mathbf{r} :

$$\mathbf{z} = [\mathbf{H}] \cdot \mathbf{r}^T$$

6. Decide:
 - ▶ If $\mathbf{z} = 0 \Rightarrow \mathbf{r}$ has no errors
 - ▶ If $\mathbf{z} \neq 0 \Rightarrow \mathbf{r}$ has errors

Syndrome-based error correction

Syndrome-based error **correction** for linear block codes:

- ▶ Syndrome $\mathbf{z} \neq 0 \Rightarrow \mathbf{r}$ has errors, we need to locate them
- ▶ The syndrome is the effect only of the error word:

$$\mathbf{z} = [\mathbf{H}] \cdot \mathbf{r}^T = [\mathbf{H}] \cdot (\mathbf{c}^T \oplus \mathbf{e}^T) = [\mathbf{H}] \cdot \mathbf{e}^T$$

7. Create a **syndrome lookup table**:

- ▶ for every possible error word \mathbf{e} , compute the syndrome $\mathbf{z} = [\mathbf{H}] \cdot \mathbf{e}^T$
- ▶ start with error words with 1 error (most likely), then with 2 errors (less likely), and so on

8. Locate the syndrome \mathbf{z} in the table, read the corresponding error word $\hat{\mathbf{e}}$

9. Find the correct word:

- ▶ adding the error word again will invert the errored bits back to the originals

$$\hat{\mathbf{c}} = \mathbf{r} \oplus \hat{\mathbf{e}}$$

Example

Example: at blackboard

Conditions on $[H]$ for error detection and correction

Conditions for syndrome-based error **detection**:

- ▶ We can detect errors if the syndrome is **non-zero**
- ▶ To detect a single error: every column of $[H]$ must be non-zero
- ▶ To detect two error: sum of any two columns of $[H]$ cannot be zero
 - ▶ that means all columns are different
- ▶ To detect n errors: sum of any n or less columns of $[H]$ cannot be zero

Conditions on $[H]$ for error detection and correction

Conditions for syndrome-based error **correction**:

- ▶ We can correct errors if the syndrome is **unique**
- ▶ To correct a single error: all columns of $[H]$ are different
 - ▶ so the syndromes, for a single error, are all different
- ▶ To correct n errors: sum of any n or less columns of $[H]$ are all different
 - ▶ much more difficult to obtain than for decoding

Rearranging the columns of $[H]$ (the order of bits in the codeword) does not affect performance

Hamming codes

- ▶ A particular class of linear error-correcting codes
- ▶ Definition: a **Hamming code** is a linear block code where the columns of $[H]$ are *the binary representation of all numbers from 1 to $2^r - 1$, $\forall r \geq 2$*
- ▶ Example (blackboard): (7,4) Hamming code
- ▶ Systematic: arrange the bits in the codeword, such that the control bits correspond to the columns having a single 1
 - ▶ no big difference from the usual systematic case, just a rearrangement of bits
 - ▶ makes implementation easier
- ▶ Example codeword for Hamming(7,4):

$$c_1 c_2 i_3 c_4 i_5 i_6 i_7$$

Properties of Hamming codes

- ▶ From definition of $[H]$ it follows:

1. Codeword has length $n = 2^r - 1$
2. r bits are parity bits (also known as **control bits**)
3. $k = 2^r - r - 1$ bits are information bits

- ▶ Notation: **(n,k) Hamming code**

- ▶ n = codeword length $= 2^r - 1$,
- ▶ k = number of information bits $= 2^r - r - 1$
- ▶ Example: (7,4) Hamming code, (15,11) Hamming code, (127,120) Hamming code

Properties of Hamming codes

- ▶ Can detect two errors
 - ▶ All columns are different \Rightarrow can detect 2 errors
 - ▶ Sum of two columns equal to a third \Rightarrow cannot correct 3

OR

- ▶ Can correct one error
 - ▶ All columns are different \Rightarrow can correct 1 error
 - ▶ Sum of two columns equal to a third \Rightarrow cannot correct 2
 - ▶ Non-systematic: syndrome = error position

BUT

- ▶ Not simultaneously!
 - ▶ same non-zero syndrome can be obtained with 1 or 2 errors, can't distinguish

Coding rate of Hamming codes

Coding rate of a Hamming code:

$$R = \frac{k}{n} = \frac{2^r - r - 1}{2^r - 1}$$

The Hamming codes can correct 1 OR detect 2 errors in a codeword of size n

- ▶ (7,4) Hamming code: $n = 7$
- ▶ (15,11) Hamming code: $n = 15$
- ▶ (31,26) Hamming code: $n = 31$

Longer Hamming codes are progressively weaker:

- ▶ weaker error correction capability
- ▶ better efficiency (higher coding rate)
- ▶ more appropriate for smaller error probabilities

Encoding & decoding example for Hamming(7,4)

See whiteboard.

In this example, encoding is done without the generator matrix G , directly with the matrix H , by finding the values of the parity bits c_1, c_2, c_4 such that

$$\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} = [H] \begin{bmatrix} c_1 \\ c_2 \\ i_3 \\ c_4 \\ i_5 \\ i_6 \\ i_7 \end{bmatrix}$$

For a single error, the syndrome **is the binary representation of the location of the error.**

Circuit for encoding Hamming(7,4)

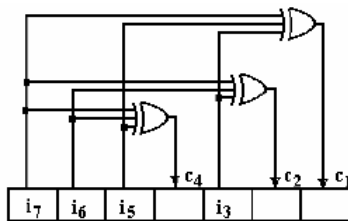


Figure 6: Hamming Encoder

- ▶ Components:
 - ▶ A **shift register** to hold the codeword
 - ▶ Logic OR gates to compute the parity bits

Circuit for decoding Hamming(7,4)

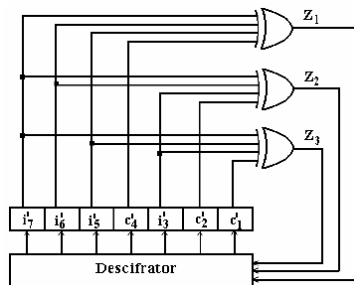


Figure 7: Hamming Encoder

- ▶ Components:
 - ▶ A **shift register** to hold the received word
 - ▶ Logic OR gates to compute the bits of the syndrome (z_i)
 - ▶ **Binary decoder**: activates the output corresponding to the binary input value, fixing the error

SECDED Hamming codes

- ▶ Hamming codes can correct 1 error OR can detect 2 errors, but we cannot differentiate the two cases

- ▶ Example:

- ▶ the syndrome $\mathbf{z} = [H] \cdot \mathbf{r}^T = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}$ can be caused by:

- ▶ a single error in location 3 (bit i_3)
 - ▶ two errors in location 1 and 2 (bits c_1 , bits c_2)
- ▶ if we know it is a single error, we can go ahead and correct it, then use the corrected data
- ▶ if we know there are two errors, we should NOT attempt to correct them, because we cannot locate the errors correctly
- ▶ Unfortunately, it is **not possible to differentiate** between the two cases.
- ▶ **Solution?** Add additional parity bit \rightarrow SECDED Hamming codes

SECDED Hamming codes

- ▶ Add an additional parity bit to differentiate the two cases
 - ▶ c_0 = sum of all n bits of the codeword
- ▶ For (7,4) Hamming codes:

$$\mathbf{c_0 c_1 c_2 i_3 c_4 i_5 i_6 i_7}$$

- ▶ The parity check matrix is extended by 1 row and 1 column

$$\tilde{H} = \begin{bmatrix} 1 & 1 \\ 0 & \mathbf{H} \end{bmatrix}$$

- ▶ Known as SECDED Hamming codes
 - ▶ **S**ingle **E**rror **C**orrection - **D**ouble **E**rror **D**etection

Encoding and decoding of SECDED Hamming codes

- ▶ Encoding:
 - ▶ compute codeword using \tilde{H}
 - ▶ alternatively, prepend $\mathbf{c}_0 = \text{sum of all other bits}$

Encoding and decoding of SECDED Hamming codes

► Decoding

- Compute syndrome of the received word using \tilde{H}

$$\tilde{\mathbf{z}} = \begin{bmatrix} z_0 \\ \mathbf{z} \end{bmatrix} = [\tilde{H}] \cdot \mathbf{r}^T$$

- z_0 is an additional bit in the syndrome corresponding to c_0
- z_0 tells us whether the received c_0 matches the parity of the received word
 - $z_0 = 0$: the additional parity bit c_0 matches the parity of the received word
 - $z_0 = 1$: the additional parity bit c_0 does not match the parity of the received word

Encoding and decoding of SECDED Hamming codes

- ▶ Decoding (continued):
 - ▶ Decide which of the following cases happened:
 - ▶ If no error happened: $z_1 = z_2 = z_3 = 0, z_0 = \forall$
 - ▶ If 1 error happened: syndrome is non-zero, $z_0 = 1$ (does not match)
 - ▶ If 2 errors happened: syndrome is non-zero, $z_0 = 0$ (does match, because the two errors cancel each other out)
 - ▶ If 3 errors happened: same as 1, can't differentiate
- ▶ Now can simultaneously differentiate between:
 - ▶ 1 error: \rightarrow perform correction
 - ▶ 2 errors: \rightarrow detect, but do not perform correction
- ▶ Also, if correction is never attempted, can detect up to 3 errors
 - ▶ minimum Hamming distance = 4 (no proof given)
 - ▶ don't know if 1 error, 2 errors or 3 errors, so can't try correction

Summary until now

- ▶ Systematic codes: information bits + parity bits
- ▶ Generator matrix: use to generate codeword

$$\mathbf{i} \cdot [\mathbf{G}] = \mathbf{c}$$

- ▶ Parity-check matrix: use to check if a codeword

$$\mathbf{0} = [\mathbf{H}] \cdot \mathbf{c}^T$$

- ▶ Syndrome:

$$\mathbf{z} = [\mathbf{H}] \cdot \mathbf{r}^T$$

- ▶ Syndrome-based error detection: syndrome non-zero
- ▶ Syndrome-based error correction: lookup table
- ▶ Hamming codes: $[\mathbf{H}]$ contains all numbers $1 \dots 2^r - 1$
- ▶ SECDED Hamming codes: add an extra parity bit

Cyclic codes

Definition: **cyclic codes** are a particular class of linear block codes for which *every cyclic shift of a codeword is also a codeword*

- ▶ Cyclic shift: cyclic rotation of a sequence of bits (any direction)
- ▶ Are a particular class of linear block codes, so all the theory up to now still applies
 - ▶ they have a generator matrix, parity check matrix etc.
- ▶ But they can be implemented more efficient than general linear block codes (e.g. Hamming)
- ▶ Used **everywhere** under the common name **CRC** (**C**yclic **R**edundancy **C**heck)
 - ▶ Network communications (Ethernet), data storage in Flash memory

Usage example: Ethernet frame

- CRC codes are used in Ethernet frames:

802.3 Ethernet packet and frame structure

Layer	Preamble	Start of frame delimiter	MAC destination	MAC source	802.1Q tag (optional)	Ethertype (Ethernet II) or length (IEEE 802.3)	Payload	Frame check sequence (32-bit CRC)	Interpacket gap
	7 octets	1 octet	6 octets	6 octets	(4 octets)	2 octets	46-1500 octets	4 octets	12 octets
Layer 2 Ethernet frame			← 64-1522 octets →						
Layer 1 Ethernet packet & IPG	← 72-1530 octets →								← 12 oct. →

Figure 8: CRC value in an Ethernet frame

Binary polynomials

- ▶ Every binary sequence \mathbf{a} corresponds to a polynomial $\mathbf{a}(\mathbf{x})$ with binary coefficients

$$a_0 a_1 \dots a_{n-1} \rightarrow \mathbf{a}(\mathbf{x}) = a_0 \oplus a_1 x \oplus \dots \oplus a_{n-1} x^{n-1}$$

- ▶ Example:

$$10010111 \rightarrow 1 \oplus x^3 \oplus x^5 \oplus x^6 \oplus x^7$$

- ▶ From now on, by “codeword” we also mean the corresponding polynomial.
- ▶ Can perform all mathematical operations with these polynomials:
 - ▶ addition, multiplication, division etc. (examples)
- ▶ There are efficient circuits for performing multiplications and divisions.

Generator polynomial

Theorem:

All the codewords of a cyclic code are multiples of a certain polynomial $g(x)$, known as **generator polynomial**.

Properties of generator polynomial $g(x)$:

- ▶ The generator polynomial has first and last coefficient equal to 1.
- ▶ The generator polynomial is a factor of $X^n \oplus 1$
- ▶ The *degree* of $g(x)$ is $n - k$, where:
 - ▶ The codeword = polynomial of degree $n - 1$ (n coefficients)
 - ▶ The information polynomial = polynomial of degree $k - 1$ (k coefficients)

$$(k - 1) + (n - k) = n - 1$$

- ▶ **The degree of $g(x)$ is the number of parity bits of the code.**

Finding a generator polynomial

Theorem:

If $g(x)$ is a polynomial of degree $(n - k)$ and is a factor of $X^n \oplus 1$, then $g(x)$ generates a (n, k) cyclic code.

Example:

$$1 \oplus x^7 = (1 \oplus x)(1 \oplus x \oplus x^3)(1 \oplus x^2 \oplus x^3)$$

Each factor generates a code:

- ▶ $1 \oplus x$ generates a $(7,6)$ cyclic code
- ▶ $1 \oplus x \oplus x^3$ generates a $(7,4)$ cyclic code
- ▶ $1 \oplus x^2 \oplus x^3$ generates a $(7,4)$ cyclic code

Popular polynomials

Some popular polys are:

16 bits: (16,12,5,0)	[X25 standard]
(16,15,2,0)	["CRC-16"]
32 bits: (32,26,23,22,16,12,11,10,8,7,5,4,2,1,0)	[Ethernet]

Figure 9: Popular generator polynomials $g(x)$

- ▶ Image from http://www.ross.net/crc/download/crc_v3.txt
- ▶ Your turn: Write the polynomials in mathematical form!

Proving the cyclic property

Theorem:

- ▶ Any cyclic shift of a codeword is also a codeword.

Proof:

- ▶ Enough to consider a cyclic shift by 1 position
- ▶ Original codeword

$$c_0 c_1 c_2 \dots c_{n-1} \rightarrow \mathbf{c}(x) = c_0 \oplus c_1 x \oplus \dots \oplus c_{n-1} x^{n-1}$$

- ▶ Cyclic shift to the right by 1 position

$$c_{n-1} c_0 c_1 \dots c_{n-2} \rightarrow \mathbf{c}'(x) = c_{n-1} \oplus c_0 x \oplus \dots \oplus c_{n-2} x^{n-1}$$

- ▶ We can rewrite:

$$\begin{aligned}\mathbf{c}'(x) &= x \cdot \mathbf{c}(x) \oplus c_{n-1} x^n \oplus c_{n-1} \\ &= x \cdot \mathbf{c}(x) \oplus c_{n-1} (x^n \oplus 1)\end{aligned}$$

Proving the cyclic property

Proof (continued):

- ▶ Since $\mathbf{c}(\mathbf{x})$ is a multiple of $g(x)$, so is $x \cdot \mathbf{c}(\mathbf{x})$
- ▶ Also $(x^n \oplus 1)$ is always a multiple of $g(x)$
- ▶ \Rightarrow It follows that their sum $\mathbf{c}'(\mathbf{x})$ is also a multiple of $g(x)$, which means it is a codeword.

QED

- ▶ Note that we relied on two key facts:
 - ▶ that a codeword $\mathbf{c}(\mathbf{x})$ is always a multiple of $g(x)$
 - ▶ that $g(x)$ is a factor of $(x^n \oplus 1)$
- ▶ Therefore a cyclic code = a code where the codewords are multiples of some $g(x)$ which is a factor of $(x^n \oplus 1)$

Coding and decoding of cyclic codes

- ▶ Cyclic codes can be used for detection or correction
- ▶ In practice, they are used mostly for **detection only** (e.g. in Ethernet)
 - ▶ because there are other codes with better performance for correction
- ▶ Can be systematic / non-systematic
 - ▶ In practice, the systematic variant is much preferred
- ▶ We study coding/decoding from 3 perspectives:
 - ▶ The mathematical way, with polynomials
 - ▶ The programming way, e.g. as a programming algorithm
 - ▶ The hardware way, via schematics

1. Coding and decoding - The mathematical way

Coding

- ▶ We want to encode the **information polynomial** with k bits

$$i(x) = i_0 \oplus i_1x \oplus \dots \oplus i_{k-1}x^{k-1}$$

- ▶ **Non-systematic** codeword generation:

$$c(x) = i(x) \cdot g(x)$$

- ▶ The resulting codeword is non-systematic

Systematic coding - The mathematical way

- ▶ **Systematic** codeword generation:

$$c(x) = b(x) \oplus i(x) \cdot x^{n-k}$$

- ▶ $b(x)$ is the remainder of dividing $x^{n-k}i(x)$ to $g(x)$:

$$x^{n-k}i(x) = a(x)g(x) \oplus b(x)$$

- ▶ Proof:

$$c(x) = b(x) \oplus i(x) \cdot x^{n-k} = b(x) \oplus a(x)g(x) \oplus b(x) = a(x)g(x)$$

- ▶ the codeword is indeed a multiple of $g(x)$
- ▶ that's because we add the remainder a second time, which cancels it

Interpretation

- ▶ Note that the systematic code is composed of two parts:
 - ▶ right part: $i(x) \cdot x^{n-k} = i(x)$ shifted to the right by $(n-k)$ positions
 - ▶ Multiplying with $x^k =$ right shifting by k
 - ▶ left part: the remainder $b(x)$, which is of degree less than $(n-k)$
 - ▶ the two parts are non-overlapping
 - ▶ therefore the code is systematic (the information bits are to the right)
- ▶ The important part is $b(x)$ (the remainder) = the **CRC value**
- ▶ Examples: at blackboard

Decoding - The mathematical way

- ▶ Any codeword $\mathbf{c}(\mathbf{x})$ is a multiple of $g(x)$
- ▶ We need to check if the received $\mathbf{r}(\mathbf{x})$ still is a multiple of $g(x)$ of dividing $x^{n-k}i(x)$ to $g(x)$:
- ▶ Error detection:
 - ▶ Divide $\mathbf{r}(\mathbf{x})$ to $g(x)$:
 - ▶ If remainder of $r(x) : g(x)$ is 0 \Rightarrow it is a codeword, no errors present
 - ▶ If remainder is non-zero \Rightarrow it's not a true codeword, **errors detected**
- ▶ Error correction: use a lookup table
 - ▶ build a lookup table for all possible error words (same as with matrix codes)
 - ▶ for each error code, divide by $g(x)$ and compute the remainder
 - ▶ when the remainder is identical to the remainder obtained with $\mathbf{r}(\mathbf{x})$, we found the error word \Rightarrow correct errors
- ▶ Example: at blackboard

2. Coding and decoding - The programming way

- ▶ We will do it only for systematic codes
- ▶ We want to compute the remainder $b(x)$ of dividing $x^{n-k}i(x)$ to $g(x)$
 - ▶ the remainder will be put alongside the information word, that's easy with programming
- ▶ We want **an efficient algorithm to compute the remainder of a polynomial division**
- ▶ Different bit ordering:
 - ▶ we wrote polynomials with largest power to the right
 - ▶ but in binary, most significant bit (MSB) is to the right, LSB to the left
 - ▶ The ordering is right-to-left here, it was left-to-right in the polynomials
 - ▶ It's just a convention
- ▶ Good reference: *"A Painless Guide to CRC Error Detection Algorithms"*, Ross N. Williams
 - ▶ http://www.ross.net/crc/download/crc_v3.txt

- ▶ The mathematical polynomial division = just like XOR-ing successively with $g(x)$
 - ▶ align the binary sequence of $g(x)$ under the leftmost 1
 - ▶ XOR the sequences
 - ▶ repeat

Example

```
11010110110000
10011,.,.,.
-----,.,.,.
10011,.,.,.
10011,.,.,.
-----,.,.,.
00001,.,.,.
00000,.,.,.
-----,.,.,.
00010,.,.,.
00000,.,.,.
-----,.,.,.
00101,....
00000,....
-----,.,.,.
01011....
00000....
-----,.,.,.
10110...
10011...
```

Figure 10: Polynomial division = XORing succesively with $g(x)$

Algorithm SIMPLE

- ▶ This algorithm = “Algorithm SIMPLE”
 - ▶ Use a binary register of size $W = n - k$ bits

Load the register with zero bits.

Augment the message by appending W zero bits to the end of it.

While (more message bits)

 Begin

 Shift the register left by one bit, reading the next bit of the augmented message into register bit position 0.

 If (a 1 bit popped out of the register during step 3)

 Register = Register XOR Poly.

 End

The register now contains the remainder.

(Note: In practice, the IF condition can be tested by testing the top bit of R before performing the shift.)

Figure 11: CRC Algorithm SIMPLE

Algorithm TABLE - on whole bytes, use precomputed table

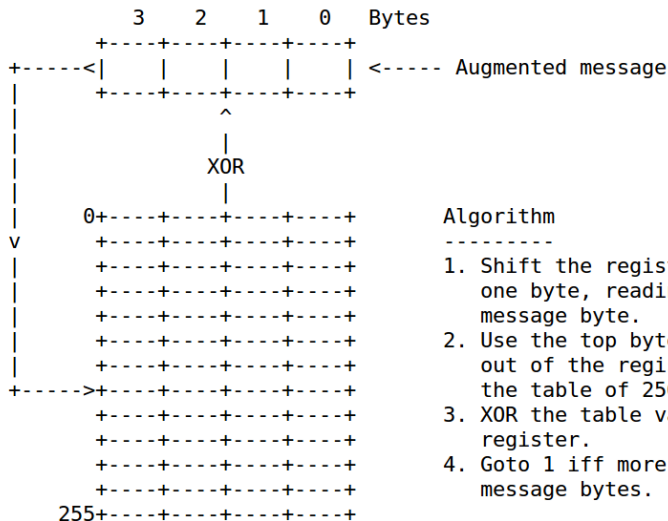
- ▶ Successive XORing with shifted $g(x)$'s = XORing with just one combined sequence
 - ▶ $((a \text{ XOR } b) \text{ XOR } c) \text{ XOR } d = a \text{ XOR } (b \text{ XOR } d \text{ XOR } c)$
- ▶ Given the first byte of $i(x)$, we can compute the combined XOR of the $g(x)$'s aligned under it (size increases with 1 byte to the right)
- ▶ The first resulting byte will be completely zero \Rightarrow can ignore it

Algorithm TABLE - on whole bytes, use precomputed table

- ▶ The first byte of $i(x)$ determines the combined $g(x)$'s sequence; from it we can ignore first byte; the rest of the bytes must be XORed with the next part of the message $i(x)$
- ▶ Can use a precomputed table of 256 values, each value having $W = k$ bytes, equal to the combined sequence of $g(x)$'s, first byte skipped

Algorithm TABLE - on whole bytes, use precomputed table

- Example for a CRC of 32 bits ($g(x)$ of degree 32)



Algorithm TABLE - on whole bytes, use precomputed table

- ▶ Algorithm implementation (pseudocode):

In C, the algorithm main loop looks like this:

```
r=0;
while (len--)
{
    byte t = (r >> 24) & 0xFF;
    r = (r << 8) | *p++;
    r^=table[t];
}
```

where len is the length of the augmented message in bytes, p points to the augmented message, r is the register, t is a temporary, and table is the computed table. This code can be made even more unreadable as follows:

```
r=0; while (len--) r = ((r << 8) | *p++) ^ t[(r >> 24) & 0xFF];
```

Figure 13: CRC Algorithm TABLE

- ▶ Error detection: two possibilities:
 - ▶ recompute the CRC value from the received $i(x)$, check if CRC is the same:
 - ▶ If the same \Rightarrow no errors
 - ▶ If different \Rightarrow errors detected!
 - ▶ OR, equivalently, divide the whole sequence $r(x) = [i(x), b(x)]$ to $g(x)$:
 - ▶ If the remainder is 0 \Rightarrow no errors
 - ▶ If the remainder is non-zero \Rightarrow errors detected!
- ▶ Error correction:
 - ▶ Not used in practice, won't do here

3. Coding and encoding - The hardware way

- ▶ Coding = based on polynomial multiplications and divisions
- ▶ Efficient circuits for multiplication / division exist, that can be used for systematic or non-systematic codeword generation (draw on blackboard)

Circuits for multiplication of binary polynomials

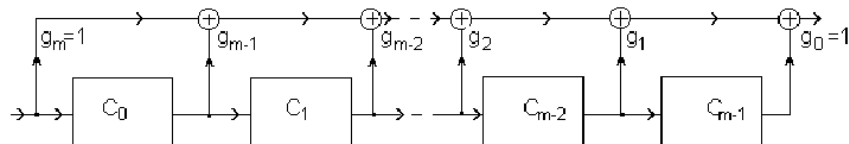


Figure 2

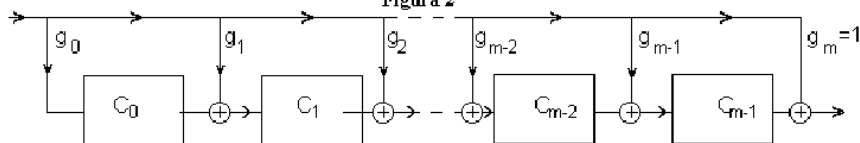


Figure 3

Figure 14: Circuits for polynomial multiplication

Operation of multiplication circuits

- ▶ The circuits multiply an input polynomial $a(x)$ with a polynomial $g(x)$ defined by their structure
- ▶ The input polynomial is applied at the input, 1 bit at a time, starting from highest degree
- ▶ The output polynomial is obtained at the output, 1 bit at a time, starting from highest degree
- ▶ Because output polynomial has larger degree, the circuit needs to operate a few more samples until the final result is obtained. During this time the input is 0.
- ▶ Examples: at the whiteboard

Circuits for division binary polynomials

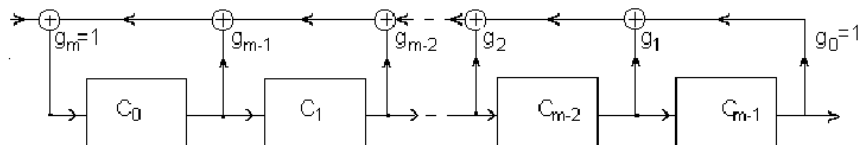


Figura 4

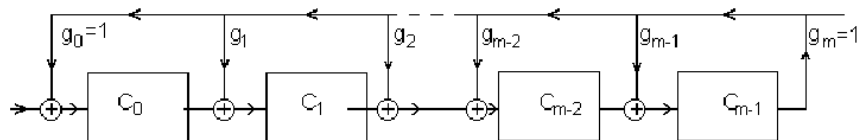


Figura 5

Figure 15: Circuits for polynomial division

Operation of division circuits

- ▶ The circuits divide an input polynomial $a(x)$ to a polynomial $g(x)$ defined by their structure
- ▶ The input polynomial is applied at the input, 1 bit at a time, starting from highest degree
- ▶ The output polynomial is obtained at the output, 1 bit at a time, starting from highest degree
- ▶ Because output polynomial has smaller degree, the circuit first outputs some zero values, until starting to output the result.
- ▶ If the remainder is 0, all the cells remain with 0 at the end
- ▶ Examples: at the whiteboard

Non-systematic cyclic encoder circuit

- ▶ Non-systematic cyclic encoder circuit:
 - ▶ simply a polynomial multiplication circuit
 - ▶ input is $i(x)$, output is $c(x)$

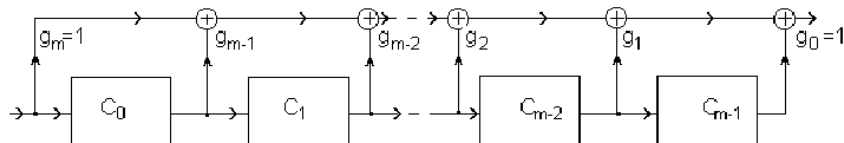


Figure 2

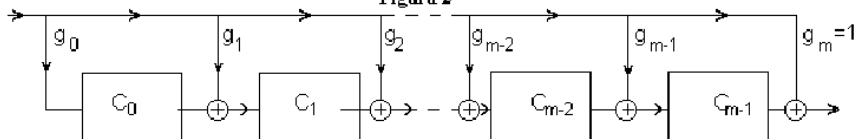


Figure 3

Figure 16: Circuits for polynomial multiplication

Systematic cyclic encoder circuit

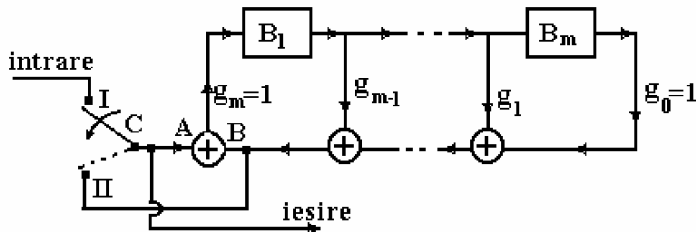


Figure 17: Systematic cyclic encoder circuit

- It contains inside a division circuit (upper right part)

Systematic cyclic encoder circuit

Operation of the cyclic encoder circuit:

- ▶ Initially all cells are 0
- ▶ Switch in position I:
 - ▶ information bits are applied to the output and to the division circuit
 - ▶ first bits of the output are the information bits \Rightarrow indeed systematic
 - ▶ the input bits are applied to the division circuit
- ▶ Switch in position II:
 - ▶ some output bits are put at the output
 - ▶ the same output bits are also applied to the input of the division circuit
- ▶ **In the end all cells end up with value 0**
 - ▶ because in phase II we add the input (A) with itself (B) at the input of the division circuit, so they cancel each other

Systematic cyclic encoder circuit

- ▶ Why is the output $c(x)$ the desired codeword? Because:
 1. has the information bits in the first part (systematic)
 2. is a multiple of $g(x)$
- ▶ Why is it a multiple of $g(x)$? Because:
 - ▶ the output $c(x)$ is always applied also to the input of the division circuit
 - ▶ in both phases of operation
 - ▶ after division, the cells end up in 0, which means there is no remainder of division
- ▶ Side note: we haven't really explained *why* the output $c(x)$ is a codeword, we just showed that it is so

The parity-check matrix for systematic cyclic codes

- ▶ Requires a more in-depth analysis of Linear Feedback Shift Registers (LFSR)

Linear-Feedback Shift Registers (LFSR)

- ▶ A **flip-flop** = a cell holding a bit value (0 or 1)
 - ▶ called "*bistabil*" in Romanian
 - ▶ operates on the edges of a clock signal
- ▶ A **register** = a group of flip-flops, holding multiple bits
 - ▶ example: an 8-bit register
- ▶ A **shift register** = a register where the output of a flip-flop is connected to the input of the next one
 - ▶ the bit sequence is shifted to the right
 - ▶ has an input (for the first cell)
- ▶ A **linear feedback shift register** (LFSR) = a shift register for which the input is computed as a linear combination of the flip-flops values
 - ▶ input = usually a XOR of some cells from the register
 - ▶ like a division circuit without any input
 - ▶ feedback = all flip-flops, with coefficients g_i in general
 - ▶ example at whiteboard

States and transitions of LFSR

- ▶ **State** of the LFSR = the sequence of bit values it holds at a certain moment (in order: right to left)
- ▶ The state at the next moment, $S(k+1)$, can be computed by multiplication of the current state $S(k)$ with the **companion matrix** (or **transition matrix**) $[T]$:

$$S(k+1) = [T] * S(k)$$

- ▶ The companion matrix is defined based on the feedback coefficients g_i :

$$T = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \cdot & \cdot & \cdot & \dots & \cdot \\ 0 & 0 & 0 & \dots & 1 \\ g_0 & g_1 & g_2 & \dots & g_{m-1} \end{bmatrix}$$

- ▶ Note: reversing the order of bits in the state \Rightarrow transposed matrix
- ▶ Starting at time 0, then the state at time k is:

$$S(k) = [T]^k S(0)$$

Period of LFSR

- ▶ The number of states is finite \Rightarrow they must repeat at some moment
- ▶ The state equal to 0 must not be encountered (in this case the LFSR will remain 0 forever)
- ▶ The **period** of the LFSR = number of time moments until the state repeats
- ▶ If period is N , then state at time N is same as state at time 0:

$$S(N) = [T]^N S(0) = S(0),$$

which means:

$$[T]^N = I_m$$

- ▶ Maximum period is $N_{max} = 2^m - 1$ (excluding state 0), in this case the polynomial $g(x)$ is called **primitive polynomial**

LFSR with inputs

- ▶ What if the LFSR has an input added to the feedback (XOR)?
 - ▶ exactly like a division circuit
 - ▶ assume the input is a sequence a_{N-1}, \dots, a_0
- ▶ Since a LFSR is a **linear circuit**, the effect is added:

$$S(1) = [T] \cdot S(0) \oplus \begin{bmatrix} 0 \\ 0 \\ \dots \\ a_{N-1} \end{bmatrix}$$

- ▶ In general:

$$S(k_1) = [T] \cdot S(k) \oplus a_{N-k} \cdot [U],$$

where $[U]$ is:

$$[U] = \begin{bmatrix} 0 \\ 0 \\ \dots \\ 1 \end{bmatrix}$$

The parity-check matrix for systematic cyclic codes

- ▶ Cyclic codes are linear block codes, so they have a parity-check and a generator matrix
 - ▶ but it is more efficient to implement them with polynomial multiplication / division circuits
- ▶ The parity-check matrix $[H]$ can be deduced by analyzing the states of the LFSR (divider) inside the encoder:
 - ▶ it is a LFSR with feedback and input
 - ▶ the input is the codeword $c(x)$
 - ▶ do computations at whiteboard ...
 - ▶ ... arrive at expression for matrix $[H]$

The parity-check matrix for systematic cyclic codes

- ▶ The parity check matrix $[H]$ has the form

$$[H] = [U, TU, T^2U, \dots T^{n-1}U]$$

- ▶ The cyclic codeword satisfies the usual relation

$$S(n) = 0 = [H]\mathbf{c}^T$$

- ▶ In case of an error, the state at time n will be the syndrome (non-zero):

$$S(n) = [H]\mathbf{r}^T \neq 0$$

Error detection and correction capability

Theorem:

Any (n,k) cyclic code with $g(x)$ being a primitive polynomial is capable of detecting 2 errors, or of correcting 1 error

► Proof:

- $g(x)$ is primitive polynomial \Rightarrow the LSFR cycles through all possible states (non-zero)
- therefore all the columns of $[H]$ are distinct
- Use the conditions based on the columns of $[H]$ from first part of chapter
 - sum of any two columns is non-zero \Rightarrow can detect 2 errors
 - any two columns are distinct \Rightarrow can correct 1 error

Packets of errors

- ▶ Until now, we considered a single error (i.e errors appear independently)
- ▶ In real life, many times the errors appear in groups
- ▶ A **packet of errors** (*an error burst*) is a sequence of two or more **consecutive errors**
 - ▶ examples: *fading* in wireless channels
- ▶ The **length** of the packet = the number of consecutive errors

Condition on columns of $[H]$ for packets of errors

- ▶ Conditions for packets of e errors are less restrictive than for e independent errors
- ▶ Error **detection** of e independent errors:
 - ▶ sum of **any** e or fewer columns is **non-zero**
- ▶ Error **detection** of a packet of e errors
 - ▶ sum of any **consecutive** e or fewer columns is **non-zero**
- ▶ Error **correction** of e independent errors
 - ▶ sum of **any** e or fewer columns is **unique**
- ▶ Error **correction** of a packet of e errors
 - ▶ sum of any **consecutive** e or fewer columns is **unique**

Detection of packets of errors

Theorem:

Any (n,k) cyclic code is capable of detecting any error packet of length $n - k$ or less

- ▶ A large fraction of longer bursts can also be detected (but not all)
- ▶ No proof (too complicated)

Cyclic decoder implemented with LFSR

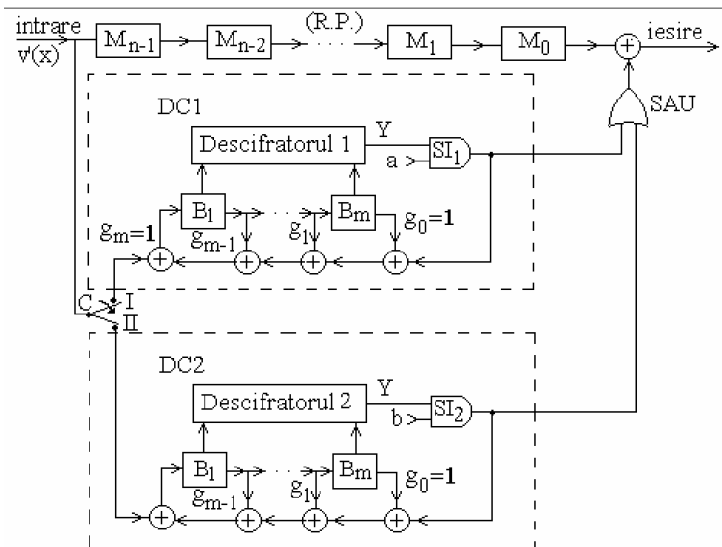


Figure 18: Cyclic decoder circuit

Cyclic decoder implemented with LFSR

- ▶ Consists of:
 - ▶ main shift register MSR
 - ▶ main switch SW
 - ▶ 2 LFSRs (divider circuits), built based on $g(x)$
 - ▶ 2 error locator blocks, one for each divider
 - ▶ 2 validation gates V1, V2, for each divider
 - ▶ output XOR gate for correcting errors

Cyclic decoder implemented with LFSR

- ▶ Operation phases:

1. Input phase: SW on position I, validation gate V1 blocked

- ▶ The received codeword $r(x)$ is received one by one, starting with largest power of x^n
 - ▶ The received codeword enters the MSR and first LFSR (divider)
 - ▶ The first divider computes $r(x) : g(x)$
 - ▶ The validation gate V1 is blocked, no output
-
- ▶ Input phase ends after n moments, the switch SW goes into position II
 - ▶ If the received word has no errors, all LFSR cells are 0 (no remainder), will remain 0, the error locator will always output 0,
 - ▶ the MSR will output the received bits unchanged

Cyclic decoder implemented with LFSR

2. Decoding phase: SW on position II, validation gate V1 open
 - ▶ LFSR keeps running with no input for n more moments
 - ▶ the MSR provides the received bits at the output, one by one
 - ▶ **exactly when the erroneous bit is at the main output of MSR, the error locator will output 1, and the output XOR gate will correct the bit (TO BE PROVEN)**
 - ▶ during this time the next codeword is loaded into MSR and into second LFSR (input phase for second LFSR)

- ▶ After n moments, the received word is fully decoded and corrected
- ▶ SW goes back into position I, the second LFSR starts decoding phase, while the first LFSR is loading the new receiver word, and so on
- ▶ **To prove:** error locator outputs 1 exactly when the erroneous bit is at the main output

Cyclic decoder implemented with LFSR

Theorem: if the k -th bit r_{n-k} from $r(x)$ has an error, the error locator will output 1 exactly after $k - 1$ moments

- ▶ That's exactly when the erroneous k -th bit will be output from MSR
 \Rightarrow will be changed back to the good value

▶ **Proof:**

1. assume error on position r_{n-k}
2. the state of the LFSR at end of phase I = syndrome = column $(n - k)$ from $[H]$

$$S(n) = [H]\mathbf{r}^T = [H]\mathbf{e}^T = T^{n-k}U$$

3. after another $k - 1$ moments, the state will be

$$T^{k-1}T^{n-k}U = T^{n-1}U$$

4. since $T^n = I_n \rightarrow T^{n-1} = T^{-1}$
5. $T^{-1}U$ is the state preceding state U , which is state

$$\begin{bmatrix} 1 \\ 0 \\ \dots \\ 0 \end{bmatrix}$$

Cyclic decoder implemented with LFSR

- ▶ Step 5 above can be shown in two ways:
 - ▶ reasoning on the circuit
 - ▶ using the definition of T^{-1}

$$T = \begin{bmatrix} g_1 & g_2 & \dots g_{m-1} & 1 & \\ 1 & 0 & \dots & 0 & 0 \\ 0 & 1 & \dots & 0 & 0 \\ \cdot & \cdot & \cdot & \dots & \cdot \\ 0 & 0 & \dots & 1 & 0 \end{bmatrix}$$

- ▶ The error locator is designed to detect this state $T^{-1}U$, i.e. it is designed as shown on blackboard
- ▶ Therefore, the error locator will correct an error
- ▶ This works only for 1 error, due to proof (1 column from $[H]$)

Summary of cyclic codes

- ▶ Generated using a generator polynomial $g(x)$
- ▶ Non-systematic:

$$c(x) = i(x) \cdot g(x)$$

- ▶ Systematic:

$$c(x) = b(x) \oplus X^{n-k}i(x)$$

- ▶ $b(x)$ is the remainder of dividing $X^{n-k}i(x)$ to $g(x)$
- ▶ A codeword is always a multiple of $g(x)$
- ▶ Error detection: divide by $g(x)$, look at remainder
- ▶ Schematics:
 - ▶ Cyclic encoder
 - ▶ Cyclic decoder with LFSR
 - ▶ Thresholding cyclic decoder
 - ▶ Encoder/decoder for packets of up to 2 errors