

Department of
Information Sciences and Telecommunications

Computer Networks – TELCOM 2310

Lecture 6
Data Link Layer
Design Issues and Protocols

Dr. Znati Lecture Notes

Data Link Control Protocol Service

- ✦ The data link layer provides reliable data transmission service over a potentially unreliable transmission link
- ✦ The basic unit of communication at the data link layer is referred as frame
 - ✦ A frame is defined as a serial block of bits containing data and control information

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Data Link Control Characteristics

- ✦ Two aspects characterize DLC protocols
 - ✦ Correctness
 - ✦ Ordered, duplicate-free, error-free frame delivery
 - ✦ Efficiency
 - ✦ How much bandwidth is wasted due to unnecessary transmission

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Data Link Control Functions

- ✦ Establish an active connection over an already existing transmission link
- ✦ Maintain a sustained exchange of data frames between the sender and the receiver
- ✦ Cope with abnormal conditions such as link failure
- ✦ Initiate the termination process to relinquish the control of the link

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Data Link Control Requirements

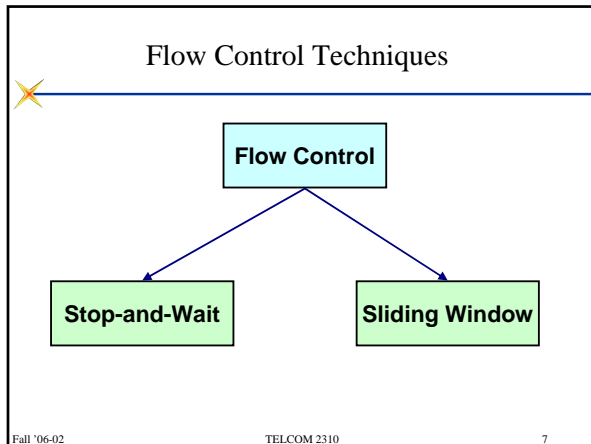
- ✦ Frame Segmentation
 - ✦ Break long streams of data into more manageable, less error prone data frames
- ✦ Frame Synchronization
 - ✦ Allow the receiver to correctly interpret transmitted data frames
 - ✦ The beginning and end of each frame must be recognizable
- ✦ Flow Control
 - ✦ Regulate the traffic to prevent the sender from overflowing the buffers of the receiver
- ✦ Error Control
 - ✦ Detect and receiver from potential frame errors
 - ✦ Commonly used error detection methods include parity bits (longitudinal and vertical), and Cyclic Redundancy Check

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Why Flow Control?

- ✦ Receiver must perform a certain amount of processing on the frame header
 - ✦ Sender may attempt to send frames faster than the receiver can process them
- ✦ Receiver may buffer incoming frames before delivery to higher-level protocols
 - ✦ Buffer may overflow if the high-level protocol user is slow in retrieving frames
- ✦ Receiver, usually switch or router, may buffer incoming frames fro retransmission on a different I/O port
 - ✦ Output buffers may overflow if the incoming flow rate exceeds the outgoing flow rate
- ✦ Flow control allows the receiver to regulate the flow of frames sent by a source and potentially limit the rate of incoming data

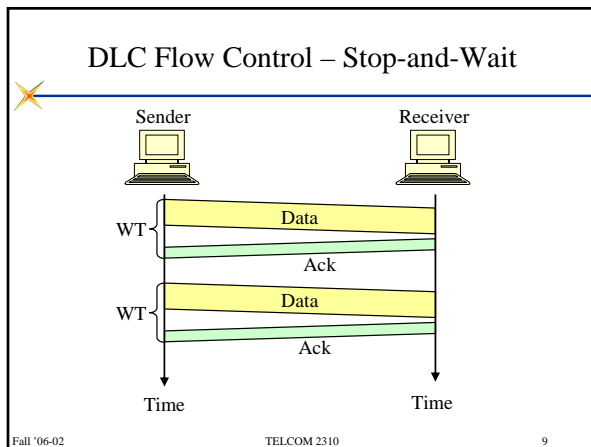
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DLC Flow Control – Stop-and-Wait

- ✘ The simplest form of flow control is *Stop-and-Wait*
- ✘ The sender transmits a frame and waits for an acknowledgement from the receiver
 - ✘ Based on the receiver's response, or lack thereof, the sender either sends the next frame or retransmits the last one
- ✘ If the two stations are simultaneously exchanging data, acknowledgments may be piggybacked in data frames

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Stop-and-Wait Flow Control

- ✘ The main advantage of Stop-and-Wait is its simplicity
- ✘ The major drawback is the time spent by the sender waiting for acknowledgments
 - ✘ The waiting time increases with the link propagation delay, causing poor performance of the scheme

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Flow Control – Sliding Window

- ✘ Sliding window protocol allows multiple frames to be in transit at one time
- ✘ Prior to data transfer, the sender and the receiver agree on an initial window size
 - ✘ The window size determines the number of frames the sender can send without waiting for an acknowledgment
- ✘ The efficiency of the sliding window protocol depends on the size of the window and the link propagation delay

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Flow Control – Window Management

- ✘ The sender maintains a sending window of the frames it is allowed to send
- ✘ The receiver maintains a receiving window of the frames it expects to receive
- ✘ Each frame is uniquely identified by a sequence number
- ✘ The receiver acknowledges frames by sending an acknowledgment containing the sequence number of the next frame expected
 - ✘ Multiple frames can be acknowledged simultaneously, as an acknowledgment containing a sequence number $N+1$ may be used to acknowledge all frames including N

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Sliding Window Parameters

- ✦ A window is characterized by
 - ✦ Upper Window Edge (UWE)
 - ✦ Lower Window Edge (LWE)
 - ✦ K , the size of the window

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Sliding Window Depiction – Sender

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Sliding Window Depiction – Receiver

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Sliding Window Dynamics

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Sliding Window Size

- ✦ Sequence numbers occupy fields of bounded size
 - ✦ A k -bit field produces a range of sequence numbers from 0 to $2^k - 1$
 - ✦ Frames are numbered modulo 2^k
- ✦ Given a k -bit sequence number field, what should be the maximum window size allowed?

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Sliding Window Size – Wrap Around

- ✦ Assume that the frame sequence numbers are modulo 2^k and the window size is 2^k
 - ✦ For $k = 3$, frame sequence numbers are modulo 8 and window size is 8
 - ✦ Sender sends frame 0 and receives Ack 1
 - ✦ Sender expands its window, sends frames 1 through 7 and 0, and receives Ack 1
 - ✦ This could mean that all eight frames were received correctly or it could mean that all 8 frames were lost
 - ✦ Limiting maximum window size to 7 eliminates this problem
- ✦ In general, if frames are numbered modulo 2^k , the maximum window can only be $2^k - 1$

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DLC Error Control

- ✘ Errors may occur during transmission
 - ✘ Lost frames fail to arrive at the destination
 - ✘ Damaged frames are not recognizable
- ✘ Automatic Repeat Request is the most common technique used to control errors over transmission links
 - ✘ Error detection
 - ✘ Positive acknowledgements are sent in response to error-free frames
 - ✘ Negative acknowledgements are sent in response to frames in error
 - ✘ Retransmission after timeouts in response to absence of acknowledgments
 - ♣ Provides recovery mechanism for deadlock situations

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Error Control

- ✘ Regardless of the desing of the transmission system, there will be errors
 - ✘ While thermal noise may be reduced to vanishingly small rates, bursty impulse noise may still result in substantial errors

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Error Control

- ✘ Errors can occur both at the bit and the packet level
 - ✘ At the bit level, bit corruption due to noise
 - ✘ At the packet level, packet loss, duplication, or delivery out of order

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Error Control

- ✘ Bit-level error control use redundancy to detect and, in some cases, correct errors
- ✘ Bit-level control is usually enforced on a hop-by-hop basis
 - ✘ Hop-by-hop error control is usually required for links with high error rates
- ✘ Higher level errors are enforced end-to-end

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Block Codes

- ✘ Block code based error control schemes use redundancy to detect errors
- ✘ The coded stream contains blocks of bits in direct correspondence to a block of data bits
 - ✘ k bits are encoded in n bits, so that $(n-k)$ bits are used for redundancy

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Error Detection Techniques – Parity Check

- ✘ The simplest error detection scheme is to append a parity bit to the end of each word in the frame
- ✘ Even Parity:
 - ✘ The parity bit, ϕ_{even} , is set as:
$$\phi_{even} = \left(\sum_{i=1}^n d_i \right) \bmod 2$$
 - ✘ d_i is the i -th data bit (0 or 1)
- ✘ Odd Parity:
 - ✘ The odd bit, is set as:
$$\phi_{even} = \left(\left(\sum_{i=1}^n d_i \right) \bmod 2 \right) \text{XOR } 1$$

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Parity Bit

- ✘ If two, or any even number of bits, are inverted, an undetected error occurs
- ✘ Another problem with the use of parity bits is that noise impulses are often long enough to destroy more than one bit, particularly at high data rates
 - ✘ May not be very effective in data communication networks

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Error Detection Techniques – Row and Column Parity

Horizontal Redundancy Check:

- ✘ Add a column $c=n+1$ such that bit $\phi_{i,c}$ is set as:

$$\phi_{i,c} = \sum_{k=1}^n d_{i,k} \bmod 2; \quad i = 1, \dots, m$$

Vertical Redundancy Check:

- ✘ Add a row $r=m+1$ such that bit $\phi_{r,j}$ is set as:

$$\phi_{r,j} = \sum_{k=1}^m d_{k,j} \bmod 2; \quad j = 1, \dots, n+1$$

- ✘ m is the number of characters and n is the number of bits per character, and $d_{i,j}$ is the bit j of character i

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VRC and HRC

Character 1	$d_{1,1}$	$d_{1,2}$	$d_{1,3}$	\dots	$d_{1,n}$	$d_{1,c}$
Character 2	$d_{2,1}$	$d_{2,2}$	$d_{2,3}$	\dots	$d_{2,n}$	$d_{1,c}$
Character 3	$d_{3,1}$	$d_{3,2}$	$d_{3,3}$	\dots	$d_{3,n}$	$d_{1,c}$
\vdots	\vdots	\vdots	\vdots	\ddots	\vdots	\vdots
Character m	$d_{m,1}$	$d_{m,2}$	$d_{m,3}$	\dots	$d_{m,n}$	$d_{m,c}$
Block Check Character	$d_{r,1}$	$d_{r,2}$	$d_{r,3}$	\dots	$d_{r,n}$	$d_{r,c}$

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Rectangular Code Reliability

1	0	1	1	0	0	1	1	0	1	1	0	0	1
0	1	1	1	0	1	0	0	1	1	1	0	1	0
1	1	0	1	0	0	1	1	0	0	1	0	0	1
0	0	0	1	0	0	1	0	0	0	1	0	0	1
0	1	1	0	1	1	0	0	0	1	0	1	1	0
0	1	0	1	1	0	1	0	1	0	1	1	0	1
0	0	1	1	0	0	0	0	0	0	1	0	0	0

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Rectangular Code Reliability

- ✘ In general, rectangular codes are easy to compute
 - ✘ They can detect and correct single bit errors
 - ✘ They can detect multiple-bit errors, but may not correct them
- ✘ Before computing the code, at least one row of bits must be accumulated in memory
 - ✘ May introduce coding delay

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Error Detection Techniques – Cyclic Codes

- ✘ The technique is known as Cyclic Redundancy Check (CRC)
 - ✘ Given a k -bit frame message, the transmitter generates an n -bit sequence, CRC, so that the resulting frame, consisting of $k+n$ bits, is exactly divisible by a generator polynomial
 - ✘ The receiver divides the incoming frame by the same generator polynomial, and if there is no remainder, assumes the message is correct

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Cyclic Codes

- ✦ The main idea is based on MOD 2 arithmetic
- ✦ Polynomials
- ✦ Shift registers and eXclusive-OR gates are needed for implementation
 - ✦ Hardware efficiency
 - ✦ Higher detection reliability

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Cyclic Codes – MOD 2 Arithmetic

- ✦ Modulo 2 arithmetic uses binary addition with no carries, which is just exclusive-or operation

$$\begin{array}{r} 1\ 1\ 1\ 1 \\ +1\ 0\ 1\ 0 \\ \hline 0\ 1\ 0\ 1 \end{array}$$

$$\begin{array}{r} 1\ 1\ 1\ 1 \\ -1\ 0\ 1\ 0 \\ \hline 0\ 1\ 0\ 1 \end{array}$$

$$\begin{array}{r} 1\ 1\ 0\ 0\ 1 \\ \times \quad \quad \quad 1\ 1 \\ \hline 1\ 1\ 0\ 0\ 1 \\ 1\ 1\ 0\ 0\ 1 \\ \hline 1\ 0\ 1\ 0\ 1\ 1 \end{array}$$

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Cyclic Codes – MOD 2 Arithmetic

- ✦ Example of division:

$$\begin{array}{r} 1\ 0\ 0\ 1\ 1\ 0 \div 1\ 0\ 1\ 1 \\ \underline{1\ 0\ 1\ 1} \\ 1\ 0\ 1\ 0 \\ \underline{1\ 0\ 1\ 1} \\ 0\ 0\ 1 \end{array}$$

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Cyclic Codes – Polynomials

- ✦ An k -bit pattern M can be represented as a polynomial $M(x)$ in the following way:

$$M(x) = \sum_{i=0}^{k-1} a_i x^i$$

- ✦ a_i denotes i -th bit of the patter M

- ✦ Example:

- ✦ $M = 10110101$

- ✦ $M(x) = x^7 + x^5 + x^4 + x^2 + 1$

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Cyclic Codes – Polynomials

- ✦ $T = (k+n)$ -bit frame to be transmitted, with $n < k$
- ✦ $M = k$ -bit message, the first k bits of T
- ✦ $F = n$ -bit FCS (Frame Check Sequence), the last n bits of T
- ✦ $P =$ Pattern of $n+1$ bits
 - ✦ P is a predetermined divisor
- ✦ The objective is to produce a frame T such that T/P has no remainder

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Cyclic Codes – Polynomials

- ✦ It should be clear that $T = 2^n M + F$
 - ✦ Multiplying M by 2^n causes it to be shifted to the left by n bits and padded with 0's
 - ✦ Adding F results in the concatenation of M and F which is T

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Cyclic Codes – Polynomials

- ✘ How must T be constructed to be exactly divisible by P ?
 - ✘ Notice that $2^n M = QP + R$, where Q is a quotient, and R is a remainder
 - ✘ Since the division is binary, the remainder is always one bit less than the divisor
 - ⚡ Therefore, use R as the Frame Check Sequence
 - ⚡ $T = 2^n M + R$
- ✘ Analogy: in decimal numbers and normal arithmetic:
 - ✘ $M = 27, P = 7 \Rightarrow 27 \cdot 10^1 / 7 \approx 38.5; R = 27 \cdot 10^1 - 39 \cdot 7 = -3$
 - ✘ $T = 27 \cdot 10^1 + 3 = 273$

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Cyclic Codes – Sending Procedure

- ✘ Given a k -bit message M , a $(n+1)$ -bit pattern P , produce the message T to be transmitted
 1. Multiply M by 2^n
 2. Divide the product by P , to produce a remainder R
 3. Add the remainder R to $2^n M$ to produce T
 4. Transmit T

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Cyclic Codes – Receiving Procedure

- ✘ Receiver receives T and divides it by P
 - ✘ If the receiver produces no remainder, it is assumed that there have been no errors
 - ✘ A non-zero remainder signals the presence of errors

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Cyclic Codes Analysis

- ✘ An error will only be undetectable if it is divisible by P
- ✘ It can be shown that all of the following are not divisible by P and hence are detectable
 - ✘ All single-bit errors
 - ✘ All double-bit errors, as long as P is at least 3 bit long
 - ✘ Any odd number of errors, as long as $P(x)$ contains a factor $(x+1)$
 - ✘ Any burst of errors for which the length of the burst is less than the length of the FCS
 - ✘ Most of large burst errors

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CRC Implementation

- ✘ The CRC process can be implemented as a dividing circuit consisting of XOR gates and a shift register
 - ✘ The shift register is a string of 1-bit storage devices,
 - ⚡ Each device has an output line which indicates the value currently stored, and an input line

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Standard Generator Polynomials

- ✘ CRC-12: $x^{12} + x^{11} + x^3 + x^2 + x + 1$
 - ✘ 1 1000 0000 1111 (0x180f)
- ✘ CRC-16: $x^{16} + x^{15} + x^2 + 1$
 - ✘ 1 1000 0000 0000 0101 (0x18005)
- ✘ CRC-ITU: $x^{16} + x^{12} + x^5 + 1$
 - ✘ 1 0001 0000 0010 0001 (0x11021)
- ✘ CRC-32: $x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x + 1$
 - ✘ 1 0000 0100 1100 0001 0001 1101 1011 0111 (0x104c11db7)

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CRC Implementation

- ✘ The circuit is implemented according to the following rules
 - ✘ The register contains n bits, equal to the length of the FCS
 - ✘ There are up to n XOR gates
 - ✘ The presence or the absence of a gate corresponds to the presence or the absence of a term in the divisor polynomial $P(x)$

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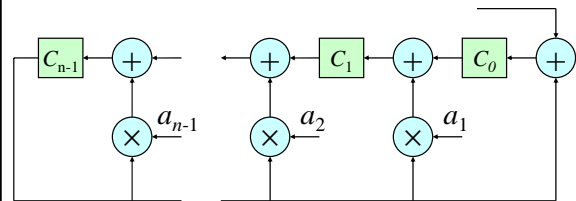
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CRC Implementation

- ✘ General CRC architecture to implement divisor

$$P(x) = 1 + a_1x + a_2x^2 + \dots + a_{n-1}x^{n-1} + x^n$$



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CRC Implementation – Example

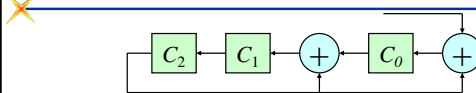
- ✘ $M(x) = x^5 + x^2 + x$
 - ✘ Message $M = 100110$
- ✘ $P(x) = x^3 + x + 1$
 - ✘ Divisor $P = 1011$
 - ✘ $n = 3, a_1 = 1, a_2 = 0$
- ✘ $R = 001$
- ✘ $T = 100110|001$

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CRC Implementation – Example



Step	C ₂	C ₁	C ₀	C ₂ ⊕C ₀	C ₂ ⊕I	I	Step	C ₂	C ₁	C ₀	C ₂ ⊕C ₀	C ₂ ⊕I	I
Init	0	0	0	0	1	1	5	1	1	1	0	1	0
1	0	0	1	1	0	0	6	1	0	1	0	1	0
2	0	1	0	0	0	0	7	0	0	1	1	0	0
3	1	0	0	1	1	1	8	0	1	0	0	0	0
4	0	1	1	1	1	1	9	1	0	0			-

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Error Correcting Code – Hamming Code

- ✘ Error correction is based on “valid codewords”
 - ✘ A valid codeword is a combination of a user’s data bits and redundant information
 - ✘ An “errored codeword” is a valid codeword with one or more corrupted bits
- ✘ A key idea in error coding is that we can NOT detect an error if it corrupts a valid codeword in such a way that the resulting codeword is identical to another valid codeword
 - ✘ Valid codewords must be distant enough so that errored codewords derived from them cannot resemble other valid codewords

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Hamming Distance

- ✘ The Hamming distance between two codewords is the minimum number of bit inversions required to transform one codeword into another
 - ✘ The Hamming distance between “101101” and “011101” is 2
- ✘ In general, to detect up to E errors, all valid codewords must be at least $E + 1$ apart from each other
 - ✘ To correct up to E errors, the minimum distance must be at least $2E + 1$

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Error Correction – Single Bit Errors

- ✘ Given any sequence of n bits, a single additional bit can detect single-bit errors
 - ✘ The additional bit is enough to distinguish between two states: error/no error
 - ✘ Not enough to correct errors
- ✘ In general, to correct a single error in a sequence of n bits, enough redundancy bits must be added to distinguish between $n + 1$ states
 - ✘ No error, error in bit 1, error in bit 2, ..., error in bit n
- ✘ How about if the errors occur in the redundancy bits?

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Redundancy Bits

- ✘ Let m be the number of data bits, and r the number of redundancy bits required to correct errors
 - ✘ Total number of bits in a codeword is $m + r$
 - ✘ r must then distinguish between $m + r + 1$ states
 - ✘ One state of no error, and $m + r$ states for errors in each location
 - ✘ r must satisfy:

$$2^r \geq m + r + 1$$

$$r \geq \log_2(m + r + 1)$$

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Hamming Code

- ✘ The question still remains how to manipulate these bits to correct errors?
 - ✘ Hamming code: perfect parity code

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Perfect Parity Code

- ✘ Let $n = m + r$ be the n -bit codeword written as:

$$b_1, b_2, \dots, b_n$$
- ✘ The r parity bits are defined as bits in positions corresponding to powers of 2:

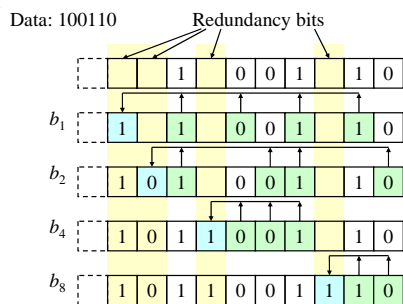
$$b_1, b_2, b_4, b_8, \dots$$
- ✘ The rule for deciding the values of the r parity bits is that the parity bit $b_k; k = 2^i$ checks all bits b_p whose bit positions p , when written in base 2 representation, have 1 in the i -th position

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Perfect Parity Code – Example

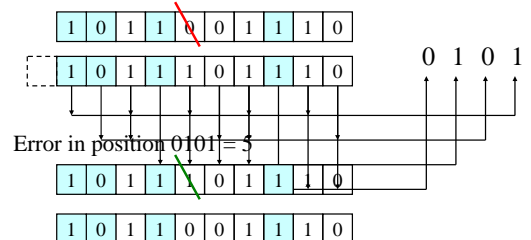


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Hamming Code – Error Checking



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Data Link Layer Protocols

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Link Layer Services

- ✦ Framing, link access:
 - ✦ encapsulate datagram into frame, adding header, trailer
 - ✦ implement channel access if shared medium (e.g., Ethernet)
 - ✦ 'physical addresses' used in frame headers to identify source, dest
 - ⊕ different from IP address!
- ✦ coordinate access to a shared medium
- ✦ reliable delivery between two physically connected devices
- ✦ flow control
- ✦ error detection/correction

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MAC Layer (Cont.)

- ✦ Base technologies
 - ✦ Frequency division multiple access (FDMA)
 - ✦ Time division multiple access (TDMA)
 - ✦ Code division multiple access (CDMA)
- ✦ Access schemes
 - ✦ Centralized
 - ⊕ GSM
 - ⊕ IS-95
 - ✦ Distributed
 - ⊕ CSMA/CD (Ethernet)
 - ⊕ CSMA/CA (wireless LAN)

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Link Layer: setting the context

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Link Layer: setting the context

- ✦ two *physically connected* devices:
 - ✦ host-router, router-router, host-host
- ✦ unit of data: *frame*

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Classes of Data Link Layer Protocols

- ✦ Based on the framing technique
 - ✦ Character oriented protocols
 - ✦ Asynchronous and Synchronous
 - Control characters are used to delimit frames and to control data interchange
 - ✦ Byte-count oriented protocols
 - ✦ A byte count is included into the frame header to determine the length of the data field
 - ✦ Bit oriented protocols
 - ✦ The objective is to achieve code independence, adaptability, high reliability, and high efficiency

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Character-Oriented Protocols – Asynchronous

- ✦ A number of asynchronous character-oriented protocols have been developed
 - ✦ Kermit
 - ✦ XMODEM, YMODEM, and ZMODEM
- ✦ No timing coordination is required between the sender and the receiver
 - ✦ Not complex
- ✦ Used mostly in modem based connections

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Character-Oriented Protocols – Synchronous

- ✦ Character-oriented DLC protocols were also developed for synchronous links
- ✦ They use special characters to delineate the various fields of a packet and to control the necessary protocol functions
 - ✦ Transparency is achieved by stuffing characters
- ✦ Bisync (Binary Synchronous Communication System – BSC) is the most popular of synchronous character-oriented protocols
 - ✦ Bisync was the de facto standard DLC protocol for synchronous communications
 - ✦ In use since 1968 between IBM computers and batch and video display terminals

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Byte-Count Oriented Protocols – DDCMP

- ✦ DDCMP – Digital's Data Communication Messages Protocol, developed by Digital Equipment Corporation
- ✦ Keep track of the "byte count"
- ✦ DDCMP can be used on synchronous or asynchronous data links, half-duplex or full-duplex transmission, serial or parallel communications, and on point-to-point or multipoint links
- ✦ Balanced protocol (i.e. no controlling station) for point to point links
- ✦ Sliding Window Go-back-N flow control

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Bit Oriented Protocols

- ✦ Currently the most implemented DLC protocols
- ✦ Bit streams not divided into characters
- ✦ Designed to satisfy a wide variety of data link requirements
 - ✦ Point-to-point and multipoint links
 - ✦ Half-duplex and full-duplex operations
 - ✦ Primary-secondary interactions
 - ✦ Links with large and small ratio of propagation time to frame transmission time

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Popular Bit Oriented DLC Protocols

- ✦ A number of very similar bit-oriented protocols have achieved widespread use
- ✦ **HDLC**, High Level Data Link Control, developed by the ISO for standardization (ISO 3309)
- ✦ **ADCCP**, Advanced Data Communication Control Procedures, developed by ANSI (ANSI X3.66) and adopted with very minor changes by the U.S. NBS (equivalent to HDLC)
- ✦ **LAP-B**, Link Access Procedures Balanced, adopted by the CCITT as a part of X.25 packet-switching network standard (subset of HDLC)
- ✦ **SDLC**, Synchronous Data Link Control, used by IBM. Not a standard, but the original bit-oriented protocol (subset of HDLC)

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Bit Stuffing – Sender’s Perspective

- ✘ Flag Fields delimit the frame at both ends with a unique pattern 01111110
 - ✘ Bit stuffing prevents this pattern from occurring in the middle of the data
- ✘ For Every sequence of five consecutive 1s of information, the sender inserts one redundant 0 after the 5th 1
 - ✘ 111111111011 ⇒ 11110111110011
 - ✘ The redundant 0 is inserted regardless of whether the sixth bit is 1 or not

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Bit Stuffing – Receiver’s Perspective

- ✘ After encountering 5 consecutive 1s, receiver looks at the sixth bit
 - ✘ If 6th bit is 0, it's destuffed and the receiver restarts counting bits
 - ✘ If 6th bit is 1, the 7th bit is checked
 - ✘ If the 7th bit is 0, the frame flag was encountered (five 1s have to be preceded by a 0 – bit stuffing)
 - ✘ If the 7th bit is 1, there is a framing error and the frame is aborted

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Characteristics of HDLC Environment

- ✘ Two link configurations
 - ✘ Unbalanced configuration, used in point-to-point and multipoint operations (not in LAP-B)
 - ✘ Balanced configuration, used only in point-to-point operation (not in SDLC)

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Internet Link Layers – PPP

- ✘ Point-to-Point Protocol, is devised to address SLIP shortcomings (RFC 1661, RFC 1662, and RFC 1663)
- ✘ PPP provides a feature-rich protocol
 - ✘ Support for multiple protocols: IP, IPX, OSI, CLNP, etc.
 - ✘ Support for error detection and control
 - ✘ Dynamic negotiation of IP addresses at the setup time
 - ✘ Support for authentication

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PPP Main Components

- ✘ Framing strategy to unambiguously delineate frames
 - ✘ Frame format also handles error detection
- ✘ A Link Control Protocol (LCP) to control line and negotiate parameters
 - ✘ Line initialization
 - ✘ Line testing
 - ✘ Line options and negotiation
 - ✘ Line termination
- ✘ A Network Layer Protocol (NCP) to negotiate network layer options
 - ✘ A different NCP is provided for each network layer supported
 - ✘ Provides independence of the network layer protocol

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PPP Typical Scenario

- ✘ PC uses modem to call ISP router
 - ✘ Physical connection is established when ISP router's modem answers
- ✘ PC sends ISP router a series of LCP packets within PPP frame(s) payload field
 - ✘ LCP packets and responses determine the PPP parameters to be used
- ✘ PC sends a series of NCP packets to configure the network layer
 - ✘ NCP for IP is used to dynamically negotiate an IP address
- ✘ NCP and LCP packets are used to tear down the network layer and data link layer connections, respectively
- ✘ Modems terminate physical link connection

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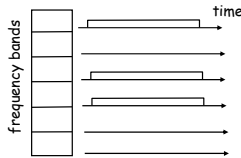
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Channel Partitioning MAC protocols: FDMA

FDMA: frequency division multiple access

- ✦ FDM (Frequency Division Multiplexing): frequency subdivided.
- ✦ channel spectrum divided into frequency bands
- ✦ each station assigned fixed frequency band
- ✦ unused transmission time in frequency bands go idle
- ✦ example: 6-station LAN, 1,3,4 have pkt, frequency bands 2,5,6 idle



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Random Access protocols

- ✦ When node has packet to send
 - ✦ transmit at full channel data rate R.
 - ✦ no *a priori* coordination among nodes
- ✦ two or more transmitting nodes -> "collision",
- ✦ random access MAC protocol specifies:
 - ✦ how to detect collisions
 - ✦ how to recover from collisions (e.g., via delayed retransmissions)
- ✦ Examples of random access MAC protocols:
 - ✦ Pure ALOHA
 - ✦ Slotted ALOHA
 - ✦ CSMA and CSMA/CD

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Pure ALOHA

- ✦ Transmit whenever a message is ready
- ✦ Retransmit when there is a collision

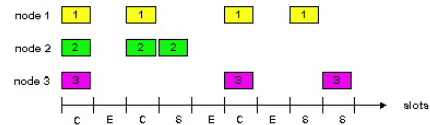
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Slotted Aloha

- ✦ time is divided into equal size slots (= pkt trans. time)
- ✦ node with new arriving pkt: transmit at beginning of next slot
- ✦ if collision: retransmit pkt in future slots with probability p , until successful.



Success (S), Collision (C), Empty (E) slots

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Slotted Aloha efficiency

Q: what is max fraction slots successful?

A: Suppose N stations have packets to send

- ✦ each transmits in slot with probability p
- ✦ prob. successful transmission S is:

by single node: $S = p(1-p)^{N-1}$

by any of N nodes

$$S = N p (1-p)^{N-1}$$

... choosing optimum p as $n \rightarrow \infty$...

$$= 1/e = .37 \text{ as } N \rightarrow \infty$$

At best: channel use for useful transmissions 37% of time!

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Problems with Pure/Slotted ALOHA

- ✦ Pure ALOHA
 - ✦ Transmit whenever a message is ready
 - ✦ Retransmit when there is a collision
- ✦ Slotted ALOHA
 - ✦ Time is divided into equal time slots
 - ✦ Transmit only at the beginning of a time slot
 - ✦ Avoid partial collisions
 - ✦ Increase delay, and require synchronization

Problem: do not listen to the channel.

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CSMA: Carrier Sense Multiple Access

CSMA: listen before transmit:

- ✦ If channel sensed idle: transmit entire pkt
- ✦ If channel sensed busy, defer transmission
 - ✦ **Persistent CSMA:** retry immediately with probability p when channel becomes idle (may cause instability)
 - ✦ **Non-persistent CSMA:** retry after random interval

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CSMA collisions

spatial layout of nodes along Ethernet

collisions can occur:
propagation delay means two nodes may not hear each other's transmission

collision:
entire packet transmission time wasted

note:
role of distance and propagation delay in determining collision prob.

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CSMA/CD (Collision Detection)

CSMA/CD: carrier sensing, deferral as in CSMA

- ✦ collisions *detected* within short time
- ✦ colliding transmissions aborted, reducing channel wastage
- ✦ persistent or non-persistent retransmission

✦ collision detection:

- ✦ easy in wired LANs: measure signal strengths, compare transmitted, received signals
- ✦ difficult in wireless LANs: receiver shut off while transmitting

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“Taking Turns” MAC protocols

channel partitioning MAC protocols:

- ✦ share channel efficiently at high load
- ✦ inefficient at low load: delay in channel access, 1/N bandwidth allocated even if only 1 active node!

Random access MAC protocols

- ✦ efficient at low load: single node can fully utilize channel
- ✦ high load: collision overhead

“taking turns” protocols
look for best of both worlds!

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“Taking Turns” MAC protocols

<p>Polling:</p> <ul style="list-style-type: none"> ✦ master node “invites” slave nodes to transmit in turn ✦ Request to Send, Clear to Send msgs ✦ concerns: <ul style="list-style-type: none"> ✦ polling overhead ✦ latency ✦ single point of failure (master) 	<p>Token passing:</p> <ul style="list-style-type: none"> ✦ control token passed from one node to next sequentially. ✦ token message ✦ concerns: <ul style="list-style-type: none"> ✦ token overhead ✦ latency ✦ single point of failure (token)
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Summary of MAC protocols

✦ What do you do with a shared media?

- ✦ Channel Partitioning, by time, frequency or code
 - ⚡ Time Division, Frequency Division, Code Division
- ✦ Random partitioning (dynamic),
 - ⚡ ALOHA, S-ALOHA, CSMA, CSMA/CD
 - ⚡ carrier sensing: easy in some technologies (wire), hard in others (wireless)
 - ⚡ CSMA/CD used in Ethernet
- ✦ Taking Turns
 - ⚡ polling from a central site, token passing

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Ethernet: uses CSMA/CD

```

A: sense channel, if idle
then {
  transmit and monitor the channel;
  If detect another transmission
  then {
    abort and send jam signal;
    update # collisions;
    delay as required by exponential backoff algorithm;
    goto A
  }
  else {done with the frame; set collisions to zero}
}
else {wait until ongoing transmission is over and goto A}
    
```

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Ethernet's CSMA/CD (more)

- ✘ **Jam Signal:** make sure all other transmitters are aware of collision; 48 bits;
- ✘ **Exponential Backoff:**
 - ✘ **Goal:** adapt retransmission attempts to estimated current load
 - ✘ heavy load: random wait will be longer
 - ✘ first collision: choose K from {0,1}; delay is K x 512 bit transmission times
 - ✘ after second collision: choose K from {0,1,2,3}...
 - ✘ after ten or more collisions, choose K from {0,1,2,3,4,...,1023}

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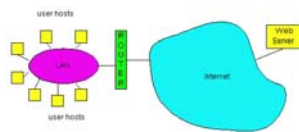
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LAN technologies

Data link layer:

- ✘ multiple access
- ✘ addressing
- ✘ error detection/correction
- ✘ Ethernet



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LAN Addresses and ARP

32-bit IP address:

- ✘ network-layer address
- ✘ used to get datagram to destination network (recall IP network definition)

LAN (or MAC or physical) address:

- ✘ used to get frame from one interface to another physically-connected interface (same network)
- ✘ 48 bit MAC address (for most LANs) burned in the adapter ROM
- ✘ WHY MAC and Internet addresses separate?
 - ✘ IP addresses depend on network that you're on
 - ✘ MAC address in hardware makes it faster
 - ✘ "Permanent" unique identifier worldwide, forever
 - ✘ ** What about networks without IP addresses? E.g. IPX, DECnet ...

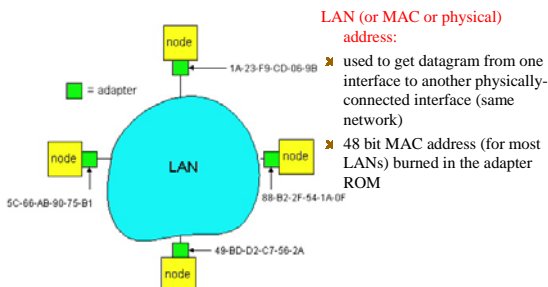
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LAN Addresses

Each adapter on LAN has unique LAN address



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LAN Address (more)

- ✘ MAC address allocation administered by IEEE
- ✘ manufacturer buys portion of MAC address space (to assure uniqueness)
- ✘ Analogy:
 - (a) MAC address: like Social Security Number
 - (b) IP address: like postal address
- ✘ MAC flat address → portability
 - ✘ can move LAN card from one LAN to another
- ✘ IP hierarchical address NOT portable
 - ✘ depends on network to which one attaches

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From IP to MAC addresses

Starting at A, given IP datagram addressed to B:

- look up net. address of B, find B on same net. as A
- link layer send datagram to B inside link-layer frame

frame source, dest address

B's MAC addr	A's MAC addr			
--------------	--------------	--	--	--

datagram source, dest address

A's IP addr	B's IP addr	IP payload
-------------	-------------	------------

← datagram →

← frame →

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ARP: Address Resolution Protocol

Question: how to determine MAC address of B given B's IP address?

- Each IP node (Host, Router) on LAN has ARP module, table
- ARP Table: IP/MAC address mappings for some LAN nodes < IP address; MAC address; TTL >
- TTL (Time To Live): time after which address mapping will be forgotten (typically 20 min)

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ARP protocol

- A knows B's IP address, wants to learn physical address of B
- A broadcasts ARP query pkt, containing B's IP address
 - all machines on LAN receive ARP query
- B receives ARP packet, replies to A with its (B's) physical layer address
- A caches (saves) IP-to-physical address pairs until information becomes old (times out)
 - soft state: information that times out (goes away) unless refreshed

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Ethernet: Case Study

"dominant" LAN technology:

- cheap \$20 for 100Mbps!
- first widely used LAN technology
- Simpler, cheaper than token LANs and ATM
- Kept up with speed race: 10, 100, 1000 Mbps

Metcalfe's Ethernet sketch

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Ethernet Frame Structure

Sending adapter encapsulates IP datagram (or other network layer protocol packet) in **Ethernet frame**

Preamble:

- 7 bytes with pattern 10101010 followed by one byte with pattern 10101011
- used to synchronize receiver, sender clock rates

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Ethernet Frame Structure (more)

- Addresses:** 6 bytes, frame is received by all adapters on a LAN and dropped if address does not match
- Type:** indicates the higher layer protocol, mostly IP but others may be supported such as Novell IPX and AppleTalk
- CRC:** checked at receiver, if error is detected, the frame is simply dropped

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Data Link Control Summary



- ✦ The data link layer provides reliable data transmission service over a potentially unreliable transmission link
 - ✦ Error handling and flow control
 - ✦ Classes of DLL protocols
- ✦ MAC Layer Protocols
 - ✦ Functionalities
 - ✦ Addressing
 - ✦ Related protocols
 - ⊕ ARP