Computer Networks COL 334/672

Link Layer

Tarun Mangla

Slides adapted from KR

Sem 1, 2024-25

Quiz on Moodle

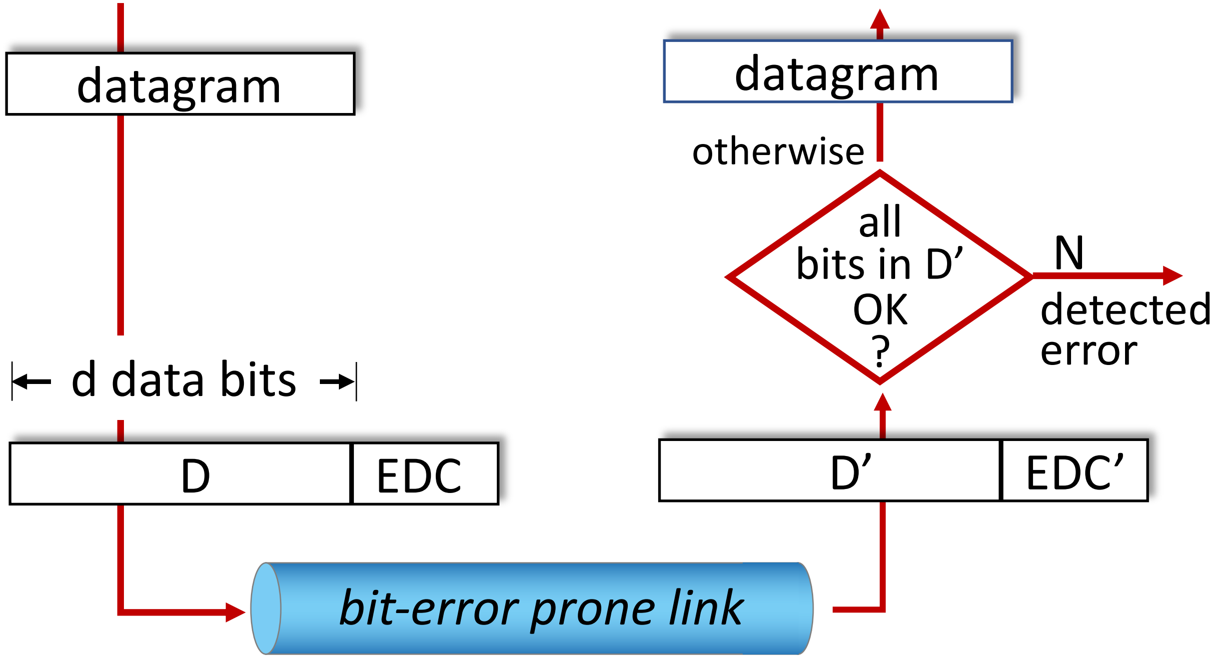
Password: wattlebird

Link Layer: Services

- Framing
- **Error detection**
- Reliability
- Link access

Error detection

EDC: error detection and correction bits (e.g., redundancy)
D: data protected by error checking, may include header fields



Error detection not 100% reliable!

- protocol may miss some errors, but rarely
- larger EDC field yields better detection and correction

Goal: maximize probability of detecting errors using only a small number of redundant bits

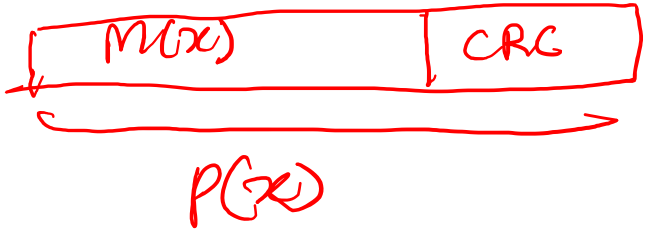
Cyclic Redundancy Check

$M(x)$: $1 \times x^3 + 0 \cdot x^2 + 1 \cdot x^1 + 1 \cdot x^0 \leftarrow 1011$

$n+1$-bit message as a polynomial of degree n

$C(x)$: divisor polynomial of degree k

$P(x)$: degree $n+1+k$



$\downarrow$

How do you generate this?

$C(x) \mid P(x)$

↳ exactly divides

Receiver:

$C(x) \mid P'(x)$

Cyclic Redundancy Check (CRC)

- Based on *finite fields*
- A message of *n+1*-bits can be represented as polynomial of degree n
- Consider:
  - M(x), a n+1 bits message to be sent
  - C(x), a divisor polynomial of degree k that is known to both sender and receiver
- Key Idea: Send P(x), n+1+k bits such that C(x) divides P(x)
  - At the receiver, if P'(x) is exactly divisible by C(x) then less likelihood of error, otherwise there is error
- How do you construct P(x) using M(x)?

Some facts [for this course!]

- Any polynomial $B(x)$ can be divided by a divisor polynomial $C(x)$ if $B(x)$ is of higher degree than $C(x)$
- Any polynomial $B(x)$ can be divided once by a divisor polynomial $C(x)$ if $B(x)$ is of the same degree as $C(x)$
- The remainder obtained when $B(x)$ is divided by $C(x)$ is obtained by performing the exclusive OR (XOR) operation on each pair of matching coefficients

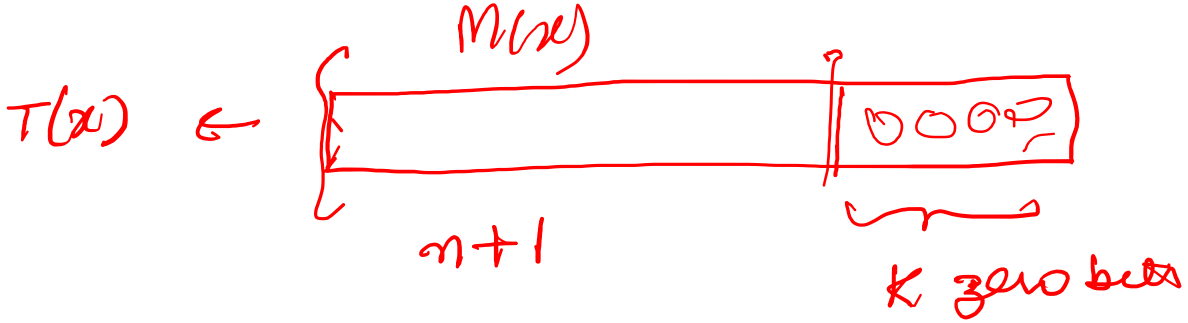
x^3+1 by x^3+x^2+1

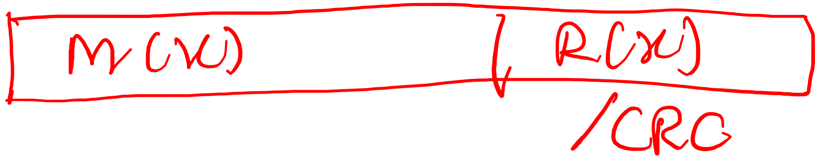
1001 1101

$$\begin{array}{r} 1 \\ 1101 \overline{)\ 1001} \\ 1101 \\ \hline 0100 \end{array}$$

Algorithm to Obtain CRC Bits

1. Multiply $M(x)$ by x^k; that is, add k zeros at the end of the message. Call this zero-extended message $T(x)$.
2. Divide $T(x)$ by $C(x)$ and find the remainder.
3. Subtract the remainder from $T(x)$.





$R(x)$: $k-1$ degree
or k bits

$T(x) = C(x) \cdot Q(x) + R(x)$

$P(x) = T(x) - R(x)$

$T(x) - R(x) = C(x) \cdot Q(x)$

Cyclic Redundancy Check (CRC): Example

- $M(x) = 101110$
- $C(x) = 1001$
- What is $P(x)$?

$T(x) = M(x) \cdot x^3$

$P(x) = T(x) - R(x)$

$= \boxed{101110}\boxed{011}$

```
        1010011
1001 ) 101110000
       1001
       ----
       00101
        0000
       ----
         1010
         1001
         ----
         001100
           1001
           ----
          01010
           1001
           ----
           0011
```

Cyclic Redundancy Check (CRC)

$P(x) + E(x) = P'(x)$

$1101 + 0001$

$\boxed{P(x)/C(x)} + \boxed{E(x)/C(x)}$

- How to pick C(x)?
  - Transmitted message: P(x) + E(x)
  - For errors to go undetected, E(x) should be divisible by C(x)
  - Pick C(x) such that above is unlikely to happen for common errors
  - Claim: Example, all single-bit errors, as long as the x^k and x^0 terms in C(x) have nonzero coefficients

$E(x) = x^i$ where $i \in \{0, \ldots, n+k\}$

Cyclic Redundancy Check (CRC)

- How to pick C(x)?
  - Transmitted message: P(x) + E(x)
  - For errors to go undetected, E(x) should be divisible by C(x)
  - Pick C(x) such that above is unlikely to happen for common errors
  - Example, all single-bit errors, as long as the x^k and x^0 terms in C(x) have nonzero coefficients

- Ethernet protocol
  - Uses a 32-bit error check

CRC-32 = $x^{32}+x^{26}+x^{23}+x^{22}+x^{16}+x^{12}+x^{11}+x^{10}+x^{8}+x^{7}+x^{5}+x^{4}+x^{2}+x+1$

- Where is CRC implemented? Hardware

Link Layer: Services

- Framing
- Error detection
- **Reliability**
- Link access

Reliability

- Error correction codes
- Acknowledgements and timeouts or Automatic Repeat request (ARQ)

Error correction code

- Also known as Forward Error Correction

- Using 2D parity

  Can detect *and* correct errors (without retransmission!)

  - detect *and correct* single bit errors

row parity

column parity

$$\begin{array}{cccc|c}
d_{1,1} & \cdots & d_{1,j} & & d_{1,j+1} \\
d_{2,1} & \cdots & d_{2,j} & & d_{2,j+1} \\
\cdots & \cdots & \cdots & & \cdots \\
d_{i,1} & \cdots & d_{i,j} & & d_{i,j+1} \\
\hline
d_{i+1,1} & \cdots & d_{i+1,j} & & d_{i+1,j+1}
\end{array}$$

no errors:

$$\begin{array}{ccccc|c}
1 & 0 & 1 & 0 & 1 & 1 \\
1 & 1 & 1 & 1 & 0 & 0 \\
0 & 1 & 1 & 1 & 0 & 1 \\
\hline
1 & 0 & 1 & 0 & 1 & 0
\end{array}$$

detected and correctable single-bit error:

$$\begin{array}{ccccc|c}
1 & 0 & 1 & 0 & 1 & 1 \\
1 & \color{red}{0} & 1 & 1 & 0 & 0 \\
0 & 1 & 1 & 1 & 0 & 1 \\
\hline
1 & 0 & 1 & 0 & 1 & 0
\end{array}$$

parity error

- Always useful?
  - When cost of retransmissions are high
  - When there are frequent bit errors

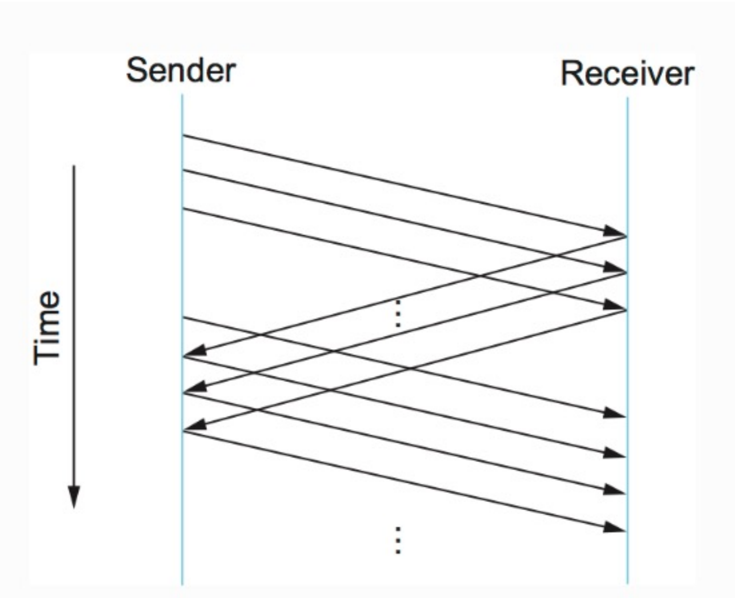
ARQ Protocol: Stop and Wait

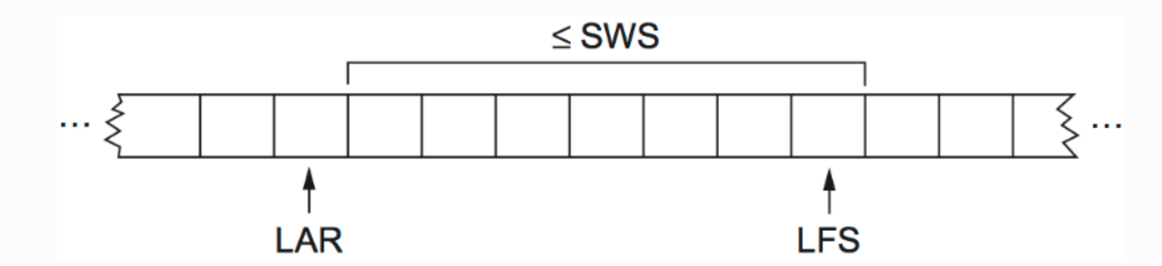
- Transmit one frame, wait for an acknowledgement
  - If no ack and timer expires, resend

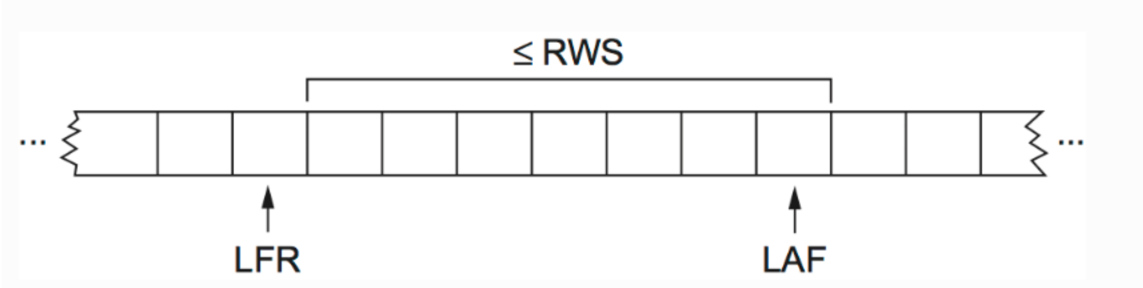
Stop and Wait

- Transmit one frame, wait for an acknowledgement
  - If no ack and timer expires, resend
- How to handle duplicate frames?
  - Sequence numbers for duplicate frames
- Any limitation?
  - Under-utilization of link
  - Example, 4 Mbps link, RTT – 10ms, Frame size – 1 KB
  - How to achieve full-link utilization?
    - Bandwidth delay product

Sliding Window Protocol







Link Layer: Services

- Framing
- Error detection
- Reliability
- **Next class: link access**

Attendance