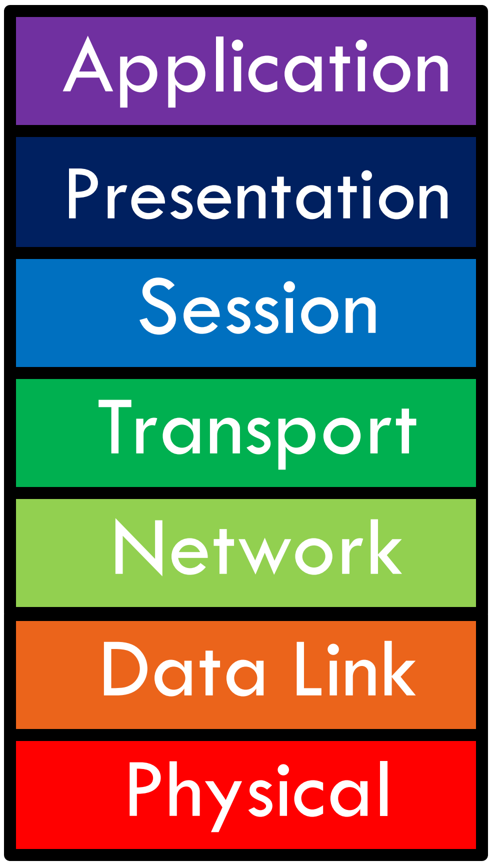
Computer Networks

Lecture 5: Data Link layer

Based on slides from D. Choffnes Northeastern U. and P. Gill from StonyBrook University

Revised Autumn 2015 by S. Laki

Data Link Layer



- Function:
  - Send blocks of data (frames) between physical devices
  - Regulate access to the physical media
- Key challenge:
  - How to delineate frames?
  - How to detect errors?
  - How to perform media access control (MAC)?
  - How to recover from and avoid collisions?

Outline

- Framing
- Error Checking and Reliability
- Media Access Control
  - 802.3 Ethernet
  - 802.11 Wifi

Framing

- Physical layer determines how bits are encoded
- Next step, how to encode blocks of data
  - Packet switched networks
  - Each packet includes routing information
  - Data boundaries must be known so headers can be read
- Types of framing
  - Byte oriented protocols
  - Bit oriented protocols
  - Clock based protocols

Byte Oriented: Byte Stuffing

- Add **FLAG** bytes as sentinel to the beginning and end of the data
- Problem: what if **FLAG** appears in the data?
  - Add a special **DLE** (Data Link Escape) character before **FLAG**
  - What if **DLE** appears in the data? Add **DLE** before it.
  - Similar to escape sequences in C
    - printf(“You must \”escape\” quotes in strings”);
    - printf(“You must \\escape\\ forward slashes as well”);
- Used by Point-to-Point protocol, e.g. modem, DSL, cellular

Byte Oriented: Byte Counting

- Sender: insert length of the data in bytes at the beginning of each frame
- Receiver: extract the length and read that many bytes
- What happens if there is an error transmitting the count field?

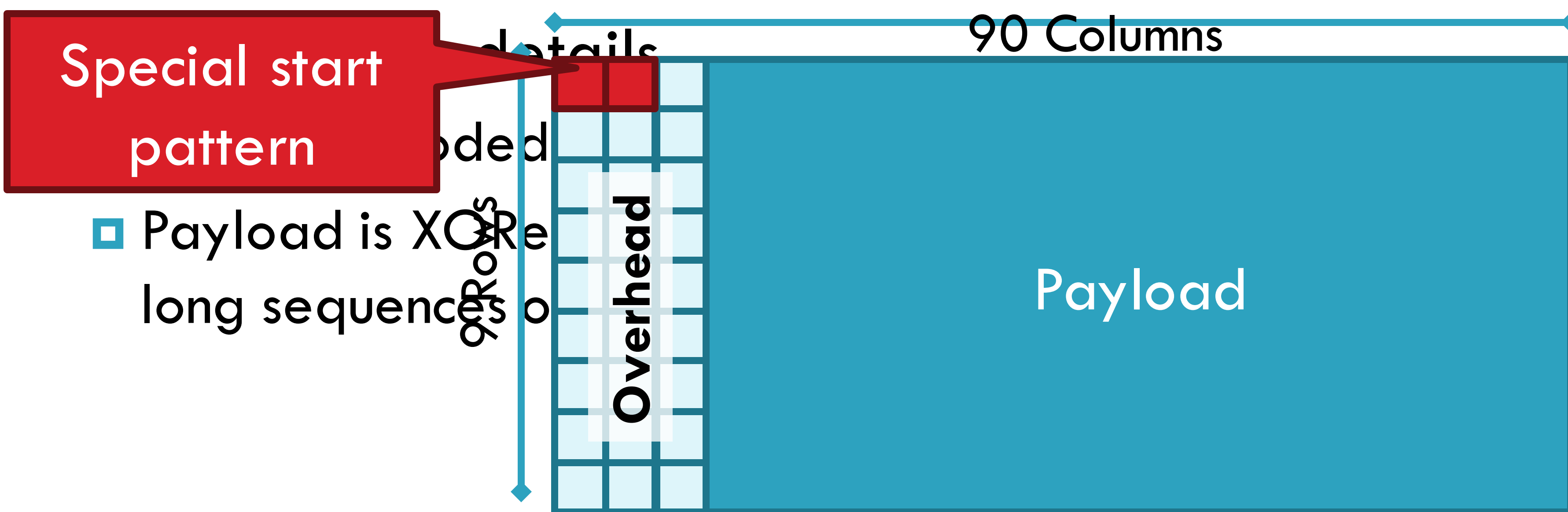
Bit Oriented: Bit Stuffing

01111110	Data	01111110

- Add sentinels to the start and end of data (similarly to byte stuffing)
  - Both sentinels are the same
  - Example: 01111110 in High-level Data Link Protocol (HDLC)
- Sender: insert a 0 after each 11111 in data
  - Known as "bit stuffing"
- Receiver: after seeing 11111 in the data…
  - 11111**0** → remove the 0 (it was stuffed)
  - 11111**1** → look at one more bit
    - 11111**10** → end of frame
    - 11111**11** → error! Discard the frame
- Disadvantage: 20% overhead at worst
- What happens if error in sentinel transmission?

Clock-based Framing: SONET

- **S**ynchronous **O**ptical **Net**work
  - Transmission over very fast optical links
  - STS-*n*, e.g. STS-1: 51.84 Mbps, STS-768: 36.7 Gbps
- STS-1 frames based on fixed sized frames
  - 9*90 = 810 bytes → after 810 bytes look for start pattern
  - ...details
  - ...oded
  - Payload is XORe... long sequence o...



Outline

- Framing
- Error Checking
- Media Access Control
  - 802.3 Ethernet
  - 802.11 Wifi

Dealing with Noise

- The physical world is inherently noisy
  - Interference from electrical cables
  - Cross-talk from radio transmissions, microwave ovens
  - Solar storms
- How to detect bit-errors in transmissions?
- How to recover from errors?

Naïve Error Detection

- Idea: send two copies of each frame
  - if (memcmp(frame1, frame2) != 0) { OH NOES, AN ERROR! }
- Why is this a bad idea?
  - Extremely high overhead
  - Poor protection against errors
    - Twice the data means twice the chance for bit errors

Parity Bits

- Idea: add extra bits to keep the number of 1s even
  - Example: 7-bit ASCII characters + 1 parity bit

0101001 1 1101001 0 1011110 1 0001110 1 0110100 1

10

- Detects 1-bit errors and some 2-bit errors
- Not reliable against bursty errors

Error control

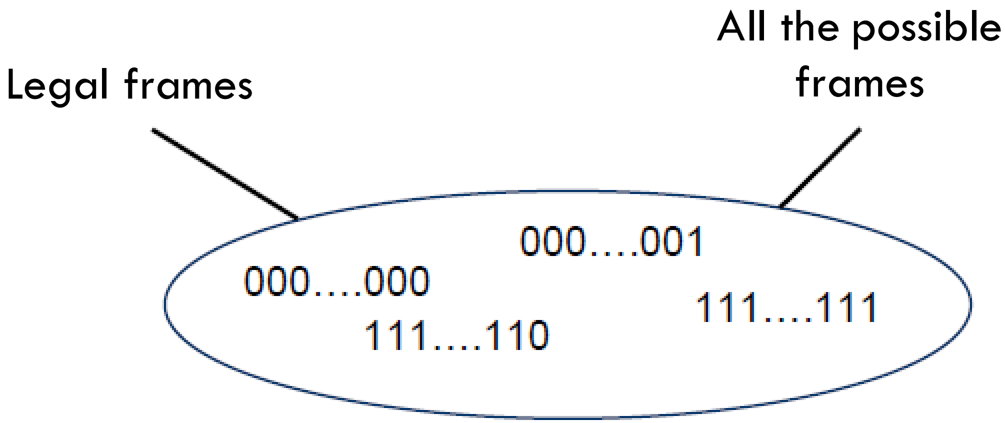
- Error Control Strategies
  - Error Correcting codes (Forward Error Correction (FEC))
  - Error detection and retransmission Automatic Repeat Request (ARQ)

Error control

- Objectives
  - Error detection
    - with correction
      - Forward error correction
    - without correction -> e.g. drop a frame
      - Backward error correction
      - The erroneous frame needs to be retransmitted
  - Error correction
    - without error detection
      - e.g. in voice transmission

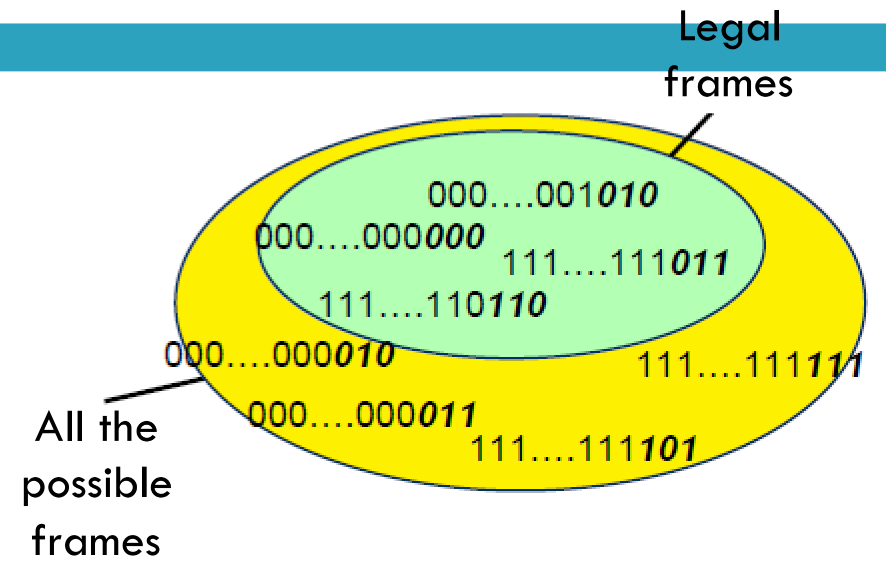
Redundancy

- Redundancy is required for error control
- Without redundancy
  - 2^m possible data messages can be represented as data on m bits
  - They all are legal!!!
  - Each error results a new legal data message
- How to detect errors???



Error-correcting codes
Redundancy

- A frame consists of
  - m data bits (message)
  - r redundant/check bits
  - The total length n = m + r



- This n-bit unit is referred to as an n-bit codeword!

Hamming distance

- The Hamming distance between two codewords is the number of differences between corresponding bits.

1. ***The Hamming distance d(000, 011) is 2 because***

$$\boxed{000 \oplus 011 \text{ is } 011 \text{ (two 1s)}}$$

2. ***The Hamming distance d(10101, 11110) is 3 because***

$$\boxed{10101 \oplus 11110 \text{ is } 01011 \text{ (three 1s)}}$$

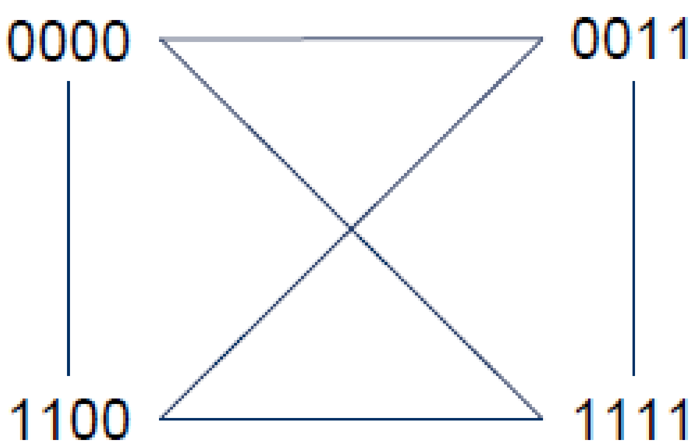
Hamming distance

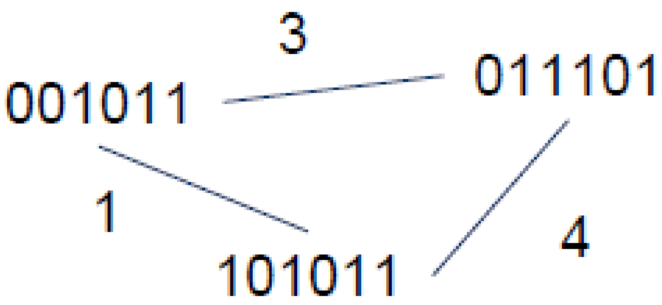
- If not all the 2^n possible codewords are used
  - Set of legal codewords =: S
- Hamming distance of the complete code
  - The smallest Hamming distance of between all the possible pairs in the set of legal codewords (S)

$$d(S) = \min_{x,y \in S, x \neq y} d(x,y)$$

What is the Hamming distance?

- Two examples:

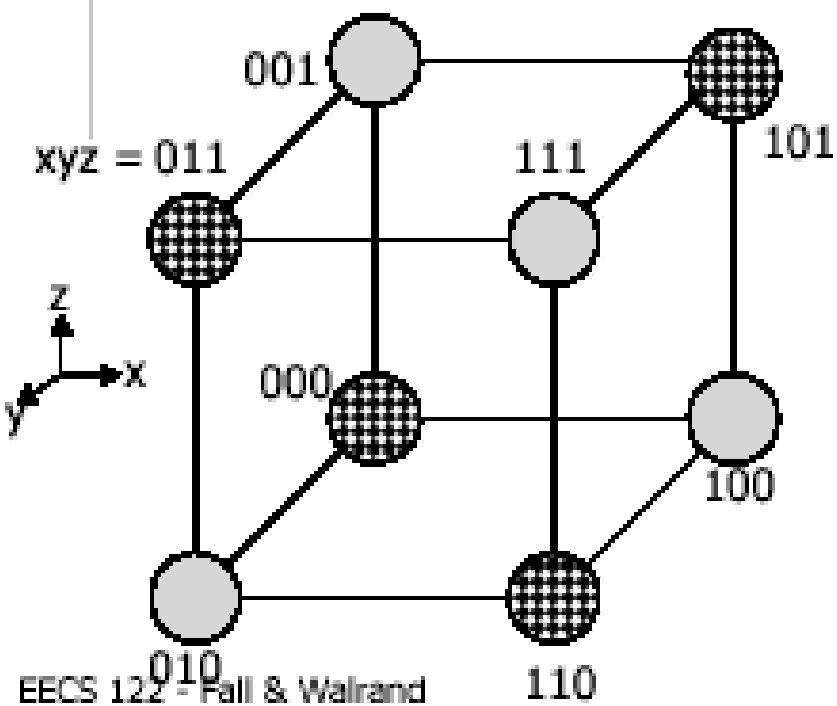




Error Control Codes

How Codes Work: Words and Codewords

- Code = subset of possible words: Codewords
- Example:
  - 3 bits => 8 words; codewords: subset



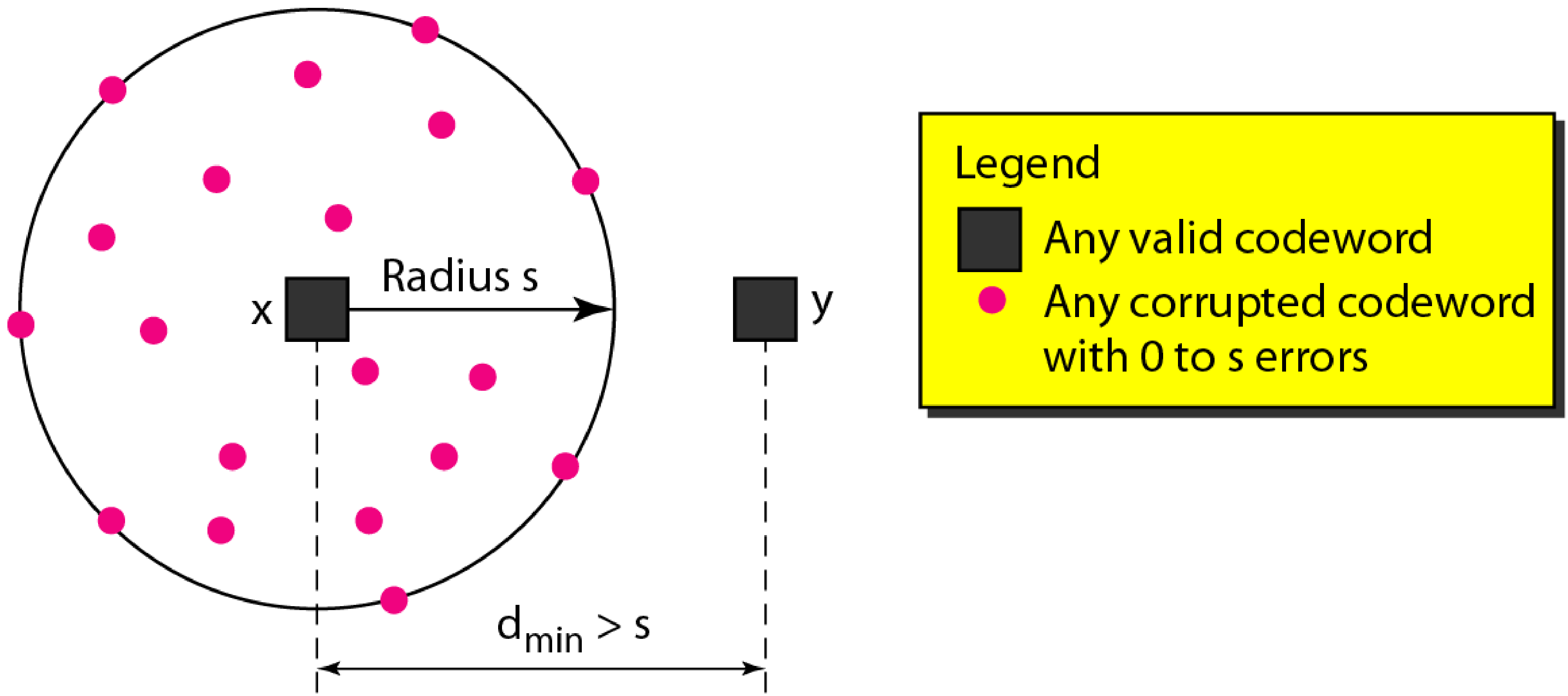
Words:
000, 001, 010, 011
100, 101, 110, 111

Code:
000, 011, 101, 110

Send only codewords

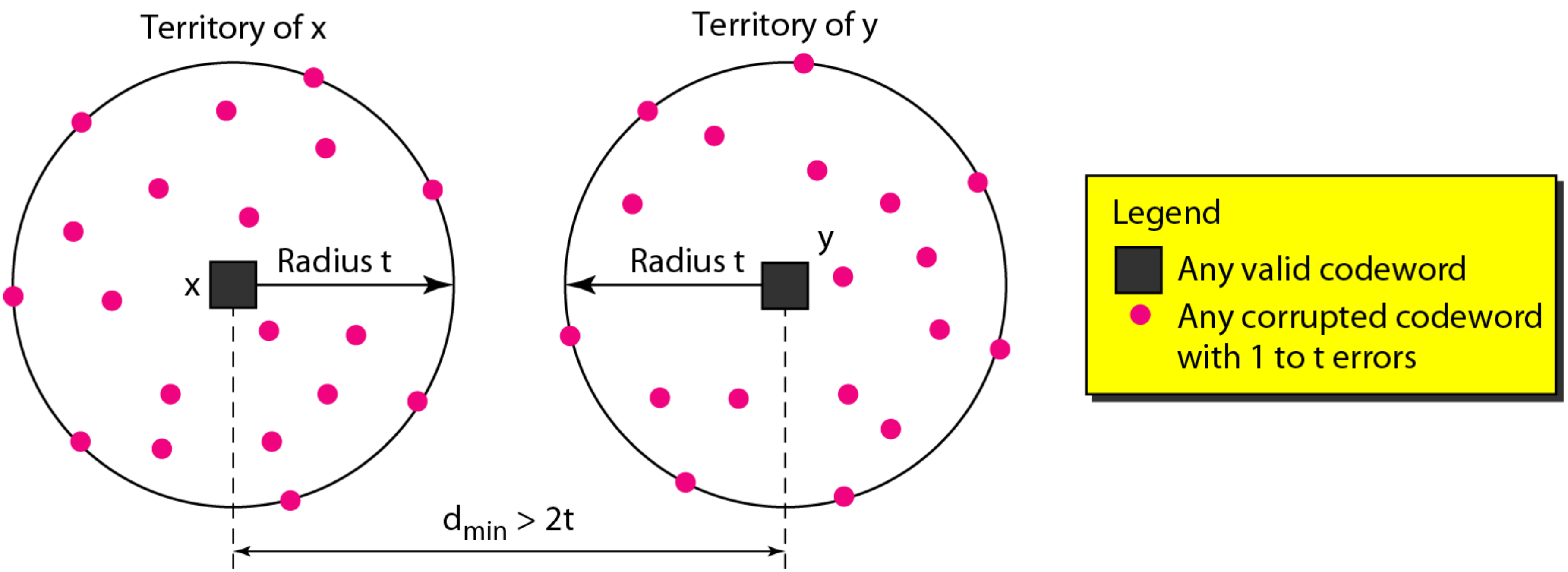
Error detection

To detect d errors, you need a distance d+1 code.



Error correction

To correct d errors, you need a distance 2d+1 code.



Example

S={ 00000000,

00001111,

11110000,

11111111

}

Parity bit – already discussed

- A single parity bit is appended to the data
  - Choosen according to the number of 1 bits in the message
    - odd or even

- An example using even parity
  - Original message: 1011010
  - A 0 bit is added to the end: 10110100
  - m=8 and r=1 in this case

- The distance of this code is 2, since any single-bit error produces a codeword with the wrong parity.

Checksums

- Idea:
  - Add up the bytes in the data
  - Include the sum in the frame

START	Data	Checksum	END

- Use ones-complement arithmetic
- Lower overhead than parity: 16 bits per frame
- But, not resilient to errors
  - Why? $\boxed{1}$101001 + $\boxed{0}$101001= 10010010
- Used in UDP, TCP, and IP

Cyclic Redundancy Check (CRC)

- Uses field theory to compute a semi-unique value for a given message

- Much better performance than previous approaches
  - Fixed size overhead per frame (usually 32-bits)
  - Quick to implement in hardware
  - Only 1 in 2^{32} chance of missing an error with 32-bit CRC

CRC (Cyclic Redundancy Check)

- Polynomial code
  - Treating bit strings as representations of polynomials with coefficients of 0 and 1.
- CRC
  - Add k bits of redundant data to an n-bit message.
  - Represent n-bit message as an n-1 degree polynomial;
    - e.g., MSG=10011010 corresponds to $M(x) = x^7 + x^4 + x^3 + x^1$.
  - Let k be the degree of some divisor polynomial G(x);
    - e.g., $G(x) = x^3 + x^2 + 1$.
    - Generator polynomial
      - Agreed upon it in advance

CRC

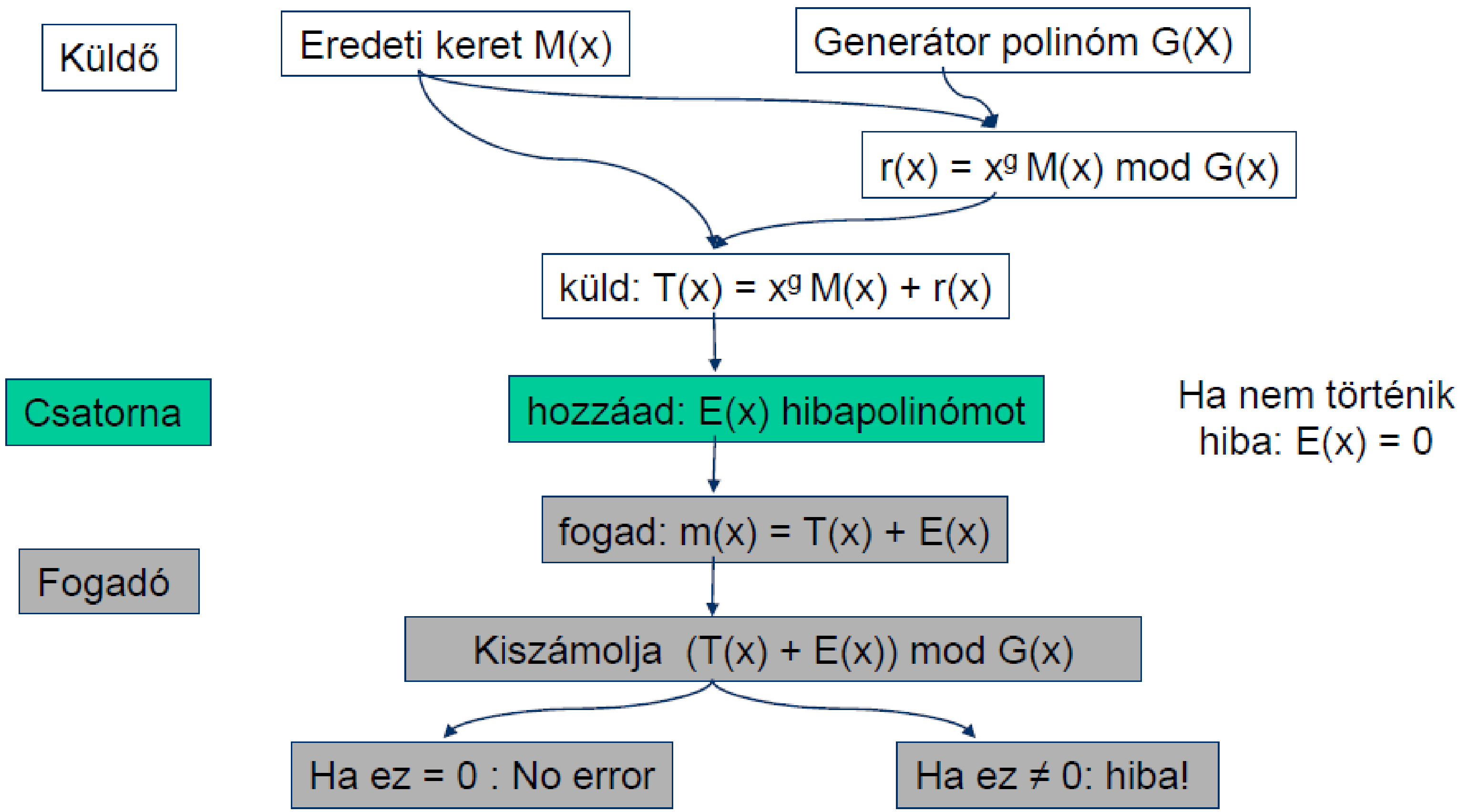
- Transmit polynomial P(x) that is evenly divisible by G(x), and receive polynomial P(x) + E(x);
  - E(x)=0 implies no errors.

- Recipient divides (P(x) + E(x)) by G(x);
  - the remainder will be zero in only two cases:
    - E(x) was zero (i.e. there was no error),
    - or E(x) is exactly divisible by C(x).

- Choose G(x) to make second case extremely rare.

CRC summary

- Source: Dr. Lukovszki Tamás



A basic example with numbers

- Make all legal messages divisible by 3
- If you want to send 10
  - First multiply by 4 to get 40
  - Now add 2 to make it divisible by 3 = 42
- When the data is received ..
  - Divide by 3, if there is no remainder there is no error
  - If no error, divide by 4 to get sent message
- If we receive 43, 44, 41, 40, then error
- 45 would not be recognized as an error

Mod 2 arithmetic

- Operations are done modulo 2

A	B	A + B
0	0	0
0	1	1
1	0	1
1	1	0

A	B	A - B
0	0	0
0	1	1
1	0	1
1	1	0

A	B	A · B
0	0	0
0	1	0
1	0	0
1	1	1

```
  0110111011
+ 1101010110
= 1011101101
```

```
 1111
+1010
=====
 0101
```

```
     11001
   x  101
    =====
     11001
+  11001
=========
   1111101
```

A basic example with polynomials

- Sender:
  - multiply $M(x) = x^7 + x^4 + x^3 + x^1$ by x^k; for our example, we get
    - $x^{10} + x^7 + x^6 + x^4$ (10011010000);
  - divide result by $C(x)$ (1101);

```
                       11111001
Generator   1101  | 10011010000    Message
                    1101
                     1001
                     1101
                      1000
                      1101
                       1011
                       1101
                        1100
                        1101
                           1000
                           1101
                            101    Remainder
```

Send 10011010000 + 101 = 10011010101, since this must be exactly divisible by $C(x)$;

Further properties

- Want to ensure that $G(x)$ does not divide evenly into polynomial $E(x)$.
- All single-bit errors, as long as the x^k and x^0 terms have non-zero coefficients.
- All double-bit errors, as long as $G(x)$ has a factor with at least three terms.
- Any odd number of errors, as long as $G(x)$ contains the factor $(x + 1)$.
- Any "burst" error (i.e sequence of consecutive errored bits) for which the length of the burst is less than k bits.
- Most burst errors of larger than k bits can also be detected.

Even Parity

Actually consists of using x+1 polynomial
Given message 0111, multiply by x to get 01110
Now divide by x+1=11

```
     0101
   ______
11 | 01110
      11
      0010
        11
         1=remainder
```

Message = 01110+1=01111 even parity

- Common polynomials for C(*x*):

CRC	$C(x)$
CRC-8	$x^8+x^2+x^1+1$
CRC-10	$x^{10}+x^9+x^5+x^4+x^1+1$
CRC-12	$x^{12}+x^{11}+x^3+x^2+x^1+1$
CRC-16	$x^{16}+x^{15}+x^2+1$
CRC-CCITT	$x^{16}+x^{12}+x^5+1$
CRC-32	$x^{32}+x^{26}+x^{23}+x^{22}+x^{16}+x^{12}+x^{11}+x^{10}+x^8+x^7+x^5+x^4+x^2+x+1$

Error control

- Error Control Strategies
  - Error Correcting codes (Forward Error Correction (FEC))
  - Error detection and retransmission Automatic Repeat Request (ARQ)

Error control

- Objectives
  - Error detection
    - with correction
      - Forward error correction
    - without correction -> e.g. drop a frame
      - Backward error correction
      - The erroneous frame needs to be retransmitted
  - Error correction
    - without error detection
      - e.g. in voice transmission

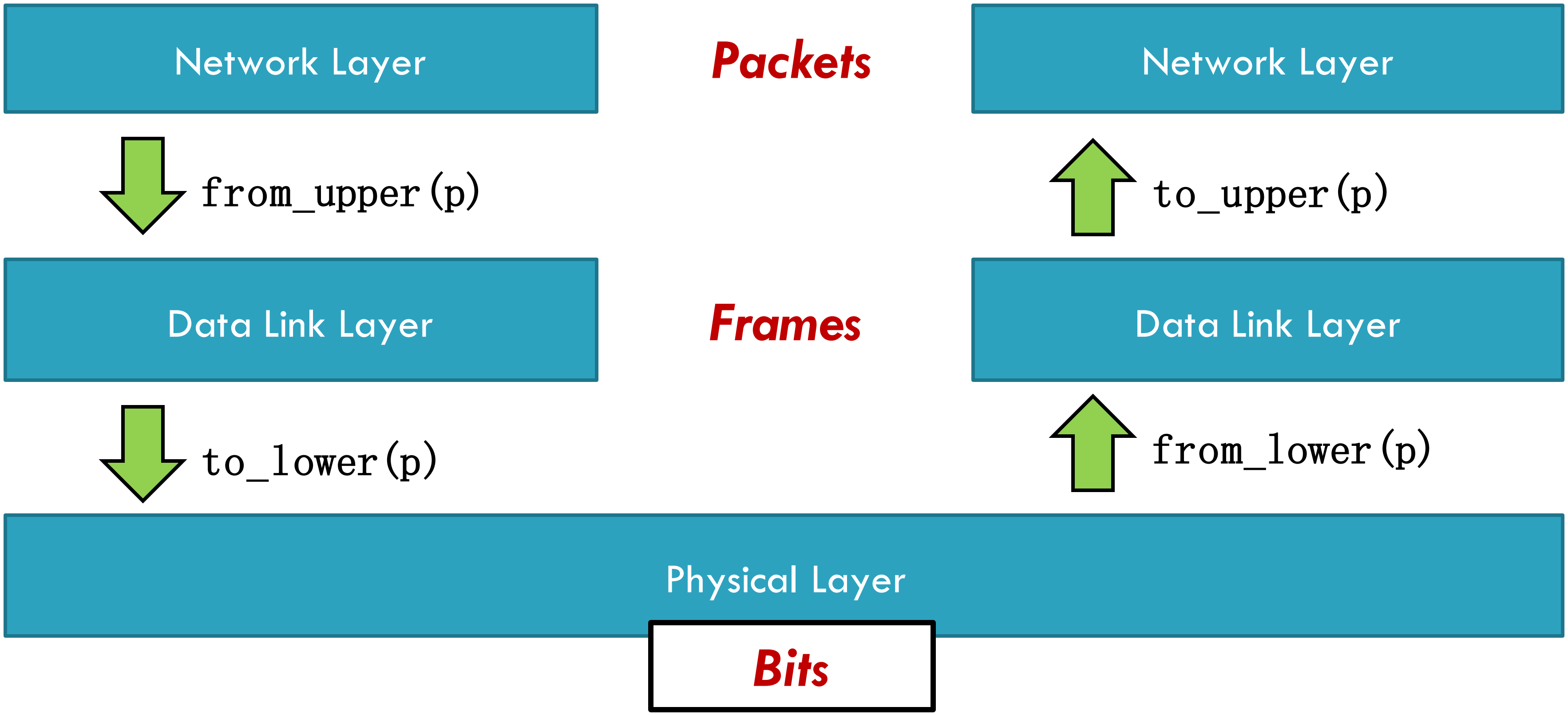
Should We Error Check in the Data Link?

- Recall the End-to-End Argument
- Cons:
  - Error free transmission cannot be guaranteed
  - Not all applications want this functionality
  - Error checking adds CPU and packet size overhead
  - Error recovery requires buffering
- Pros:
  - Potentially better performance than app-level error checking
- Data link error checking in practice
  - Most useful over lossy links
  - Wifi, cellular, satellite

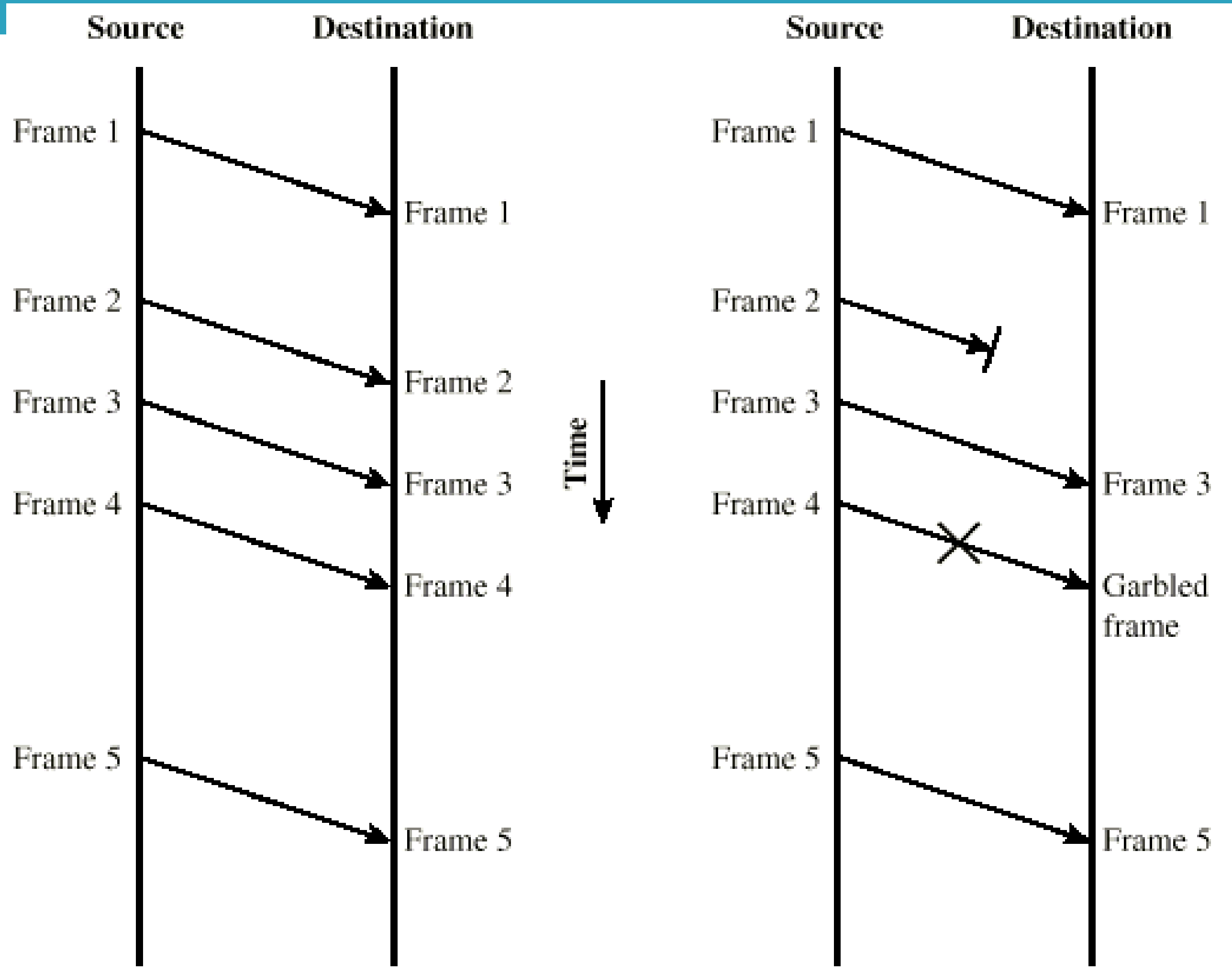
Backward Error Correction

Backward error correction

- Error detection at the receiver side
- The sender retransmits a frame until it received by the other side correctly.



Model of Frame Transmission



(a) Error-free transmission

(b) Transmission with losses and errors

Elementary Data Link Protocols

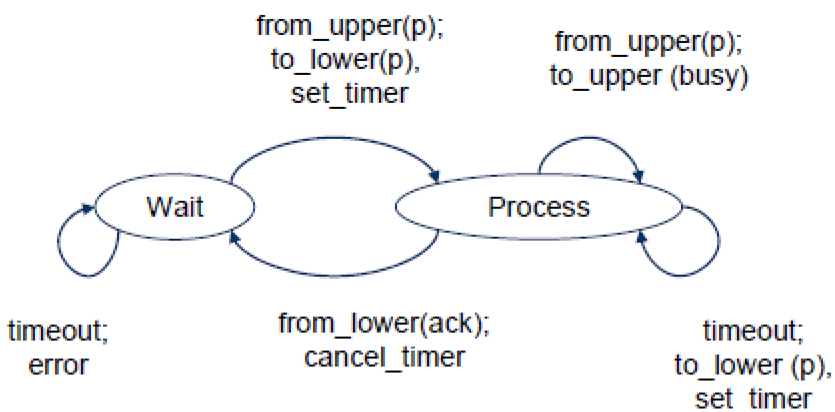
- Simplex Stop-and-Wait Protocol
- Alternate Bit Protocol
- Sliding Window Protocol

Simple Stop-and-Wait Protocol

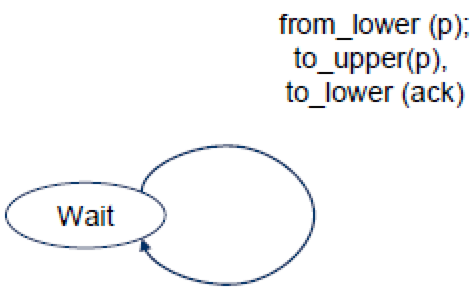
- A sends a message to B
- A stops and waits for an answer from B
  - Acknowledgement message (ACK)
- After receiving the message B sends an ACK back to the sender.
- A retransmits the message until it receives an ACK from B
- If the ACK arrived, the next message may be sent.

Simplex Stop-and-Wait Protocol

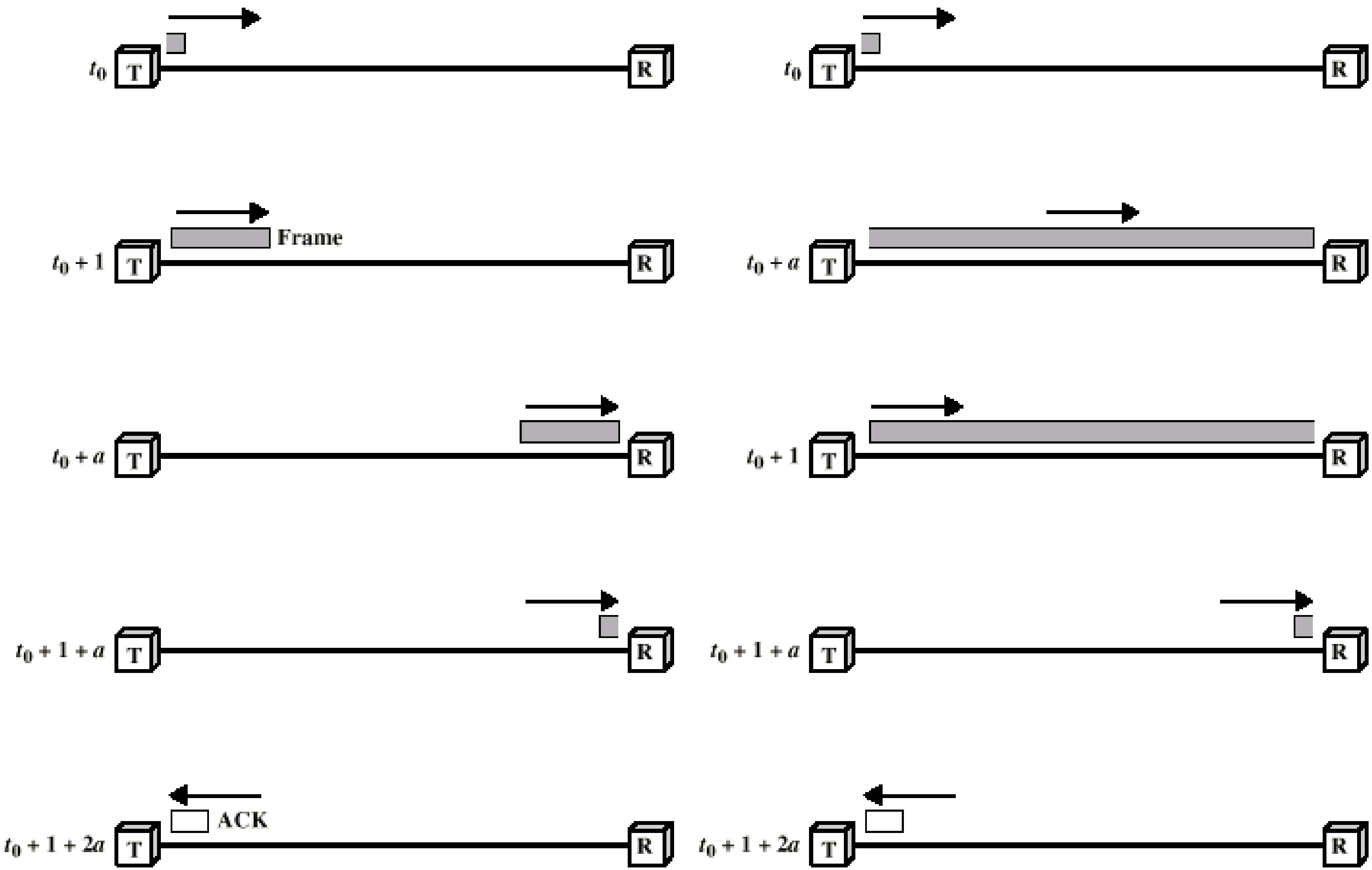
Sender



Receiver



Stop-and-Wait Link Utilization



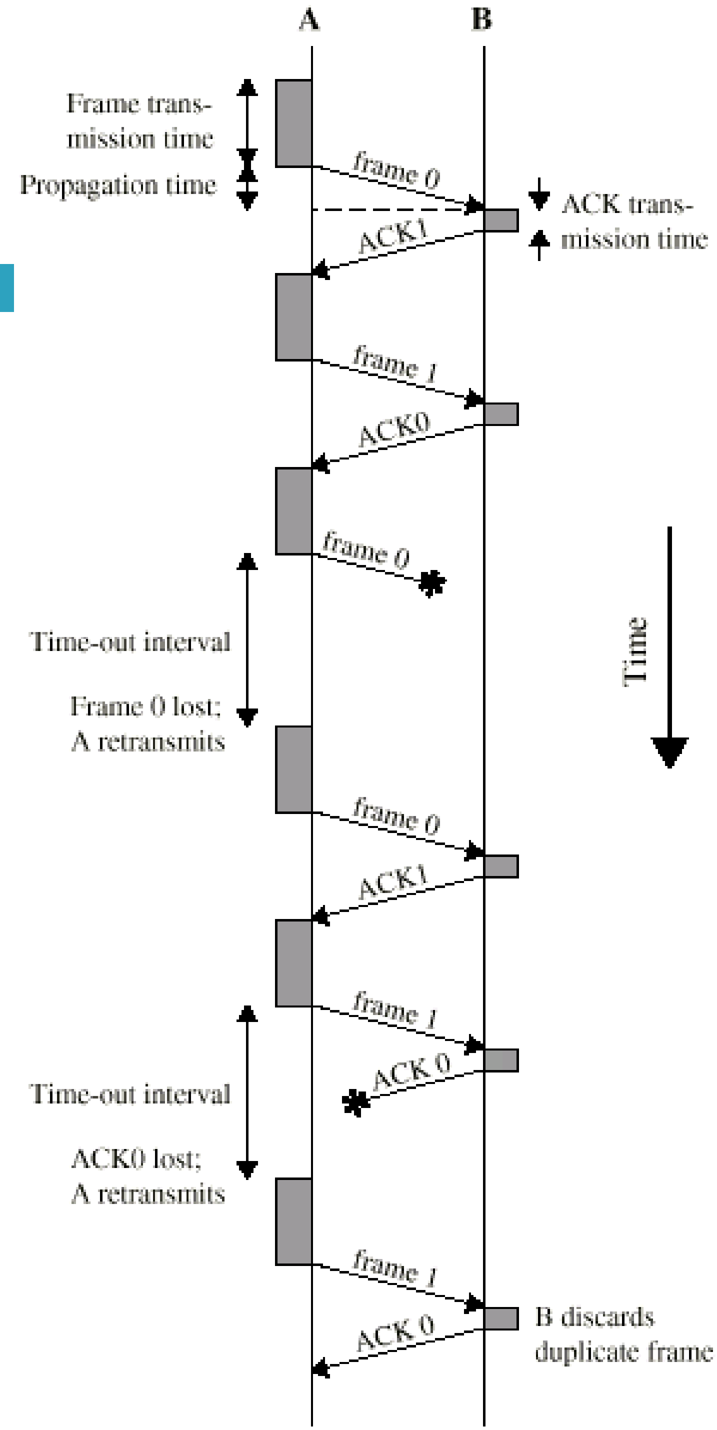
(a) $a > 1$

(b) $a < 1$

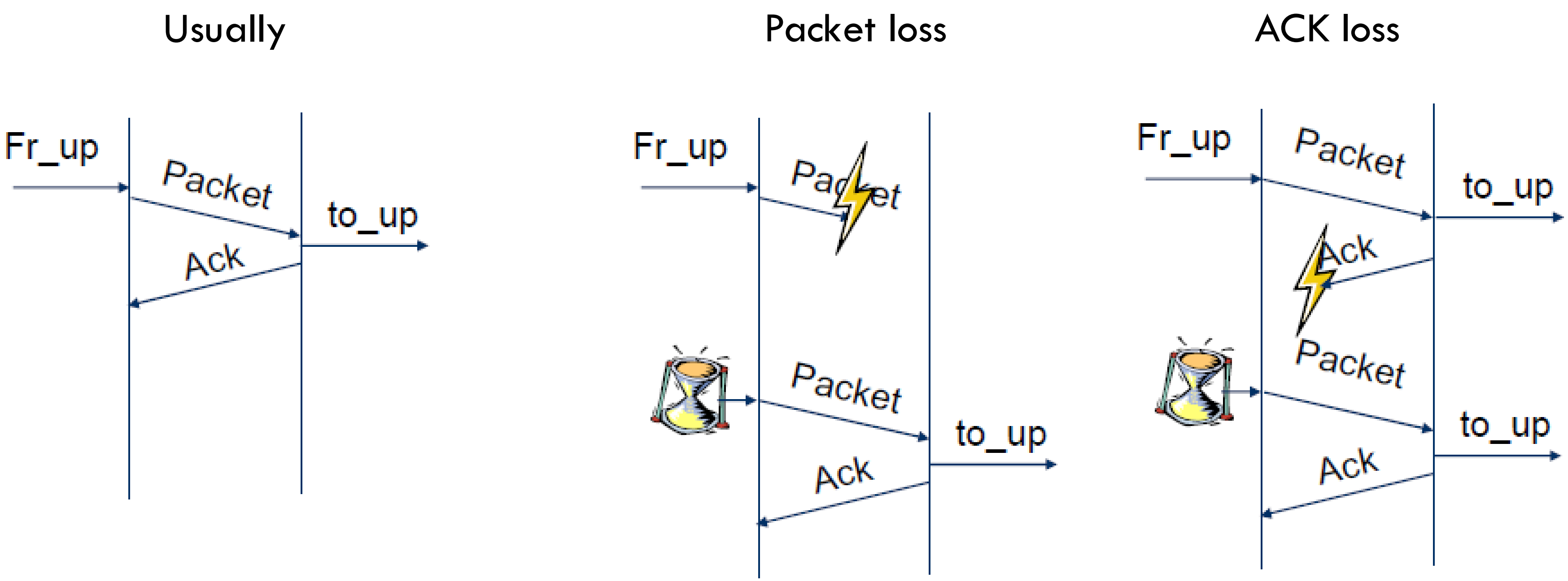
Stop-and-Wait Diagram

Simple, but inefficient for long distance and high speed applications.

We can use sliding-window technique to improve the efficiency.



What's the problem?

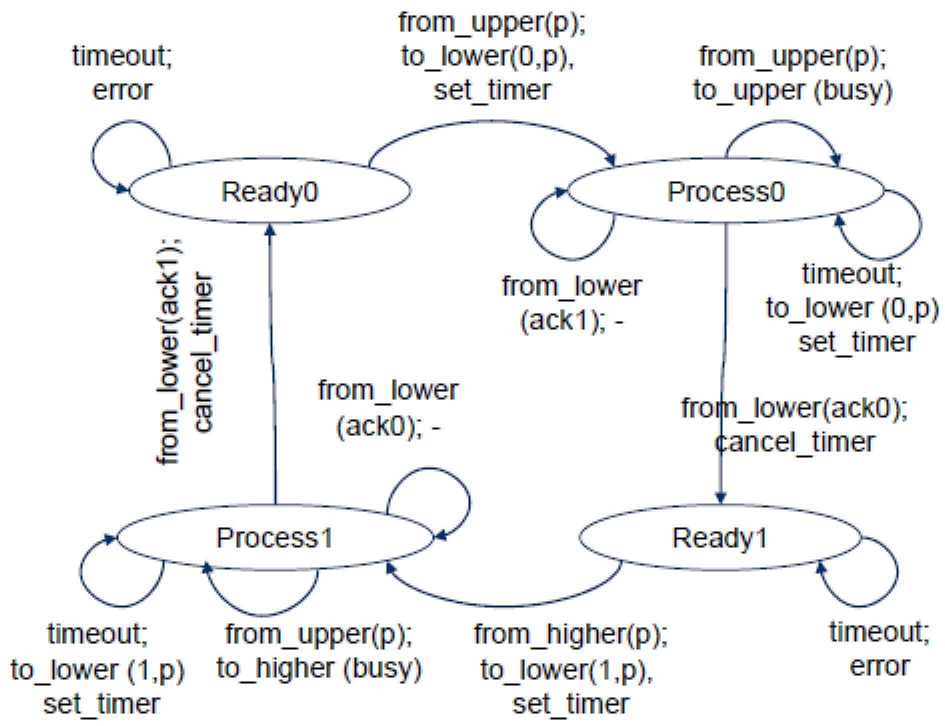


Alternating Bit Protocol (ABP)

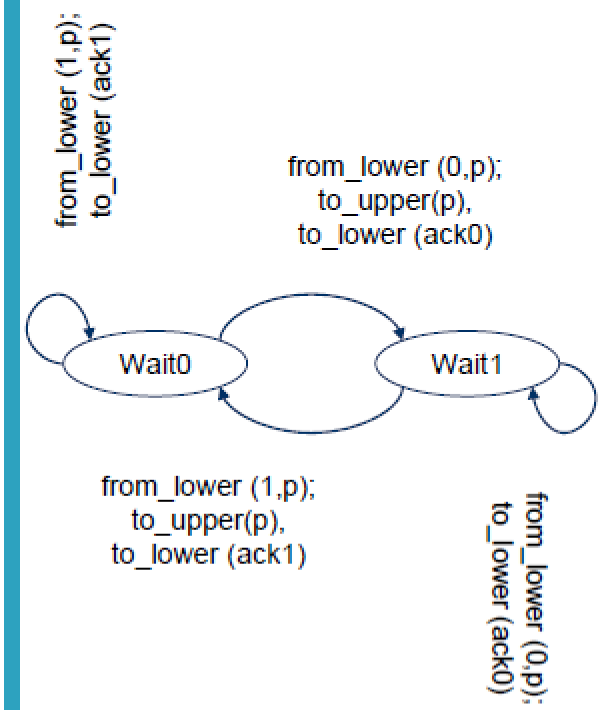
- **Let**
  - A be the sender
  - B be the receiver
- **A and B maintain internal one-bit counter**
  - A value that is 0 or 1
- **Each message from A to B contains**
  - a data part and
  - a one-bit sequence number
    - E.g. a value that is 0 or 1
- After receiving A's message, **B sends an ACK back to A**
  - which also contains a one-bit sequence number
- **Retransmission until A receives an ACK from B with the same sequence number**
  - Then A complements its sequence number
    - 0->1 or
    - 1->0

Alternating Bit Protocol (ABP)

Sender



Receiver

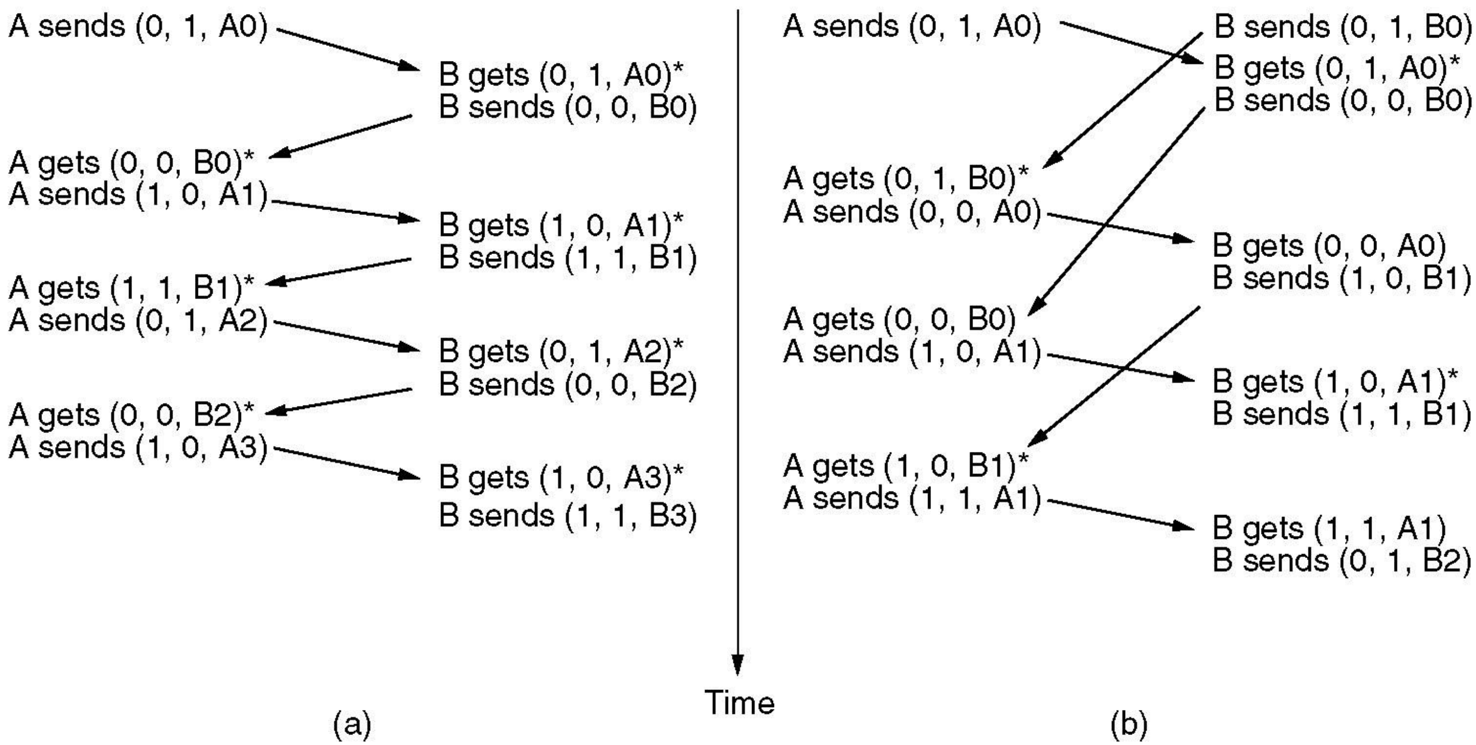


Alternating Bit Protocol (ABP)

- A reliable data transport over a noisy channel
- Basic flow control
  - The sender has to wait for the ACK from the receiver before sending the next message
- Automatic Repeat reQest (ARQ) protocol

- An acknowledgement
  - marks that the new message has been delivered.
  - allows the sender to tranmit the next frame.

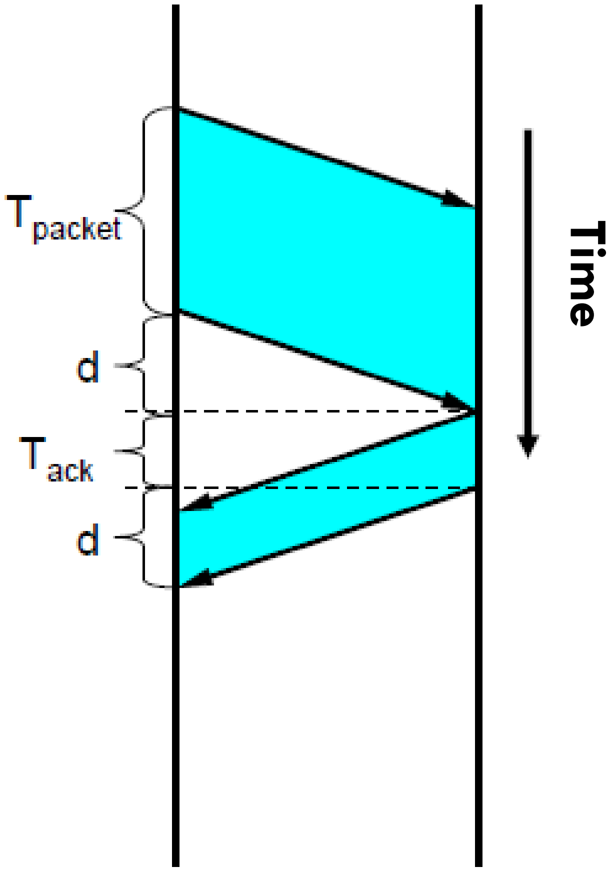
Alternating Bit Protocol



Two scenarios for ABP. (a) Normal case. (b) Abnormal case. The notation is (seq, ack, packet number). An asterisk indicates where a network layer accepts a packet.

ABP – Channel utilization

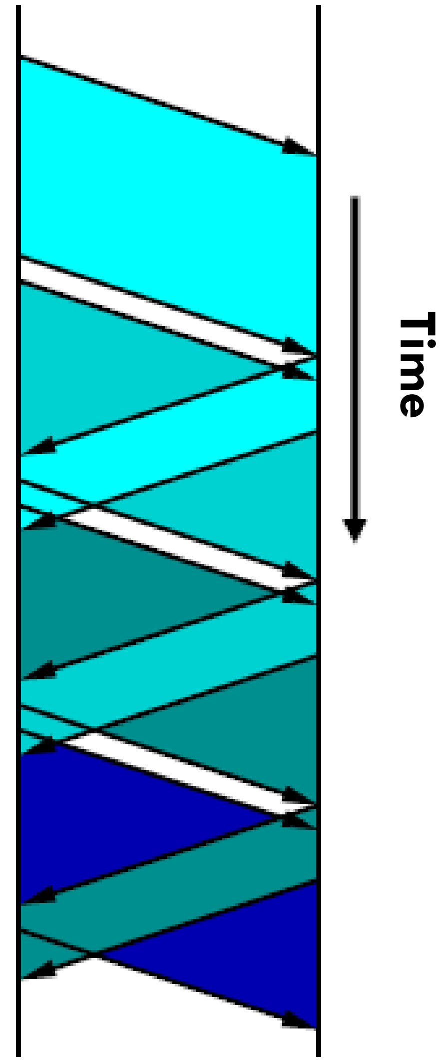
- Utilization (η) is the ratio of
  - The time needed for the transmission of a frame (T_{packet})
  - The time ellapsed until the next frame can be transmitted
    - In the fig.: (T_{packet} + d + T_{ack} + d)
- Now:
  - $\eta = T_{packet} / (T_{packet} + d + T_{ack} + d)$
- If the propagation delay is large, the ABP is not efficient.



How to improve the efficency?

- The sender transmit frames continously one after another
  - More frames are sent out, but not acknowledged.
  - Pipeline technique

- Introduce sequence numbers



Sliding Window Protocols

- Similar to ABP
- but allow multiple frames to transmit
  - Receiver has a buffer of W frames
  - Sender can send up to W frames without receiving ACK
- Bidirectional

- Each outgoing frame contains a seq. number from 0 to 2^n-1.
  - So it fits in an n-bit field
  - ABP uses n=1

- Each ACK carries the sequence number of the next expected frame by the receiver

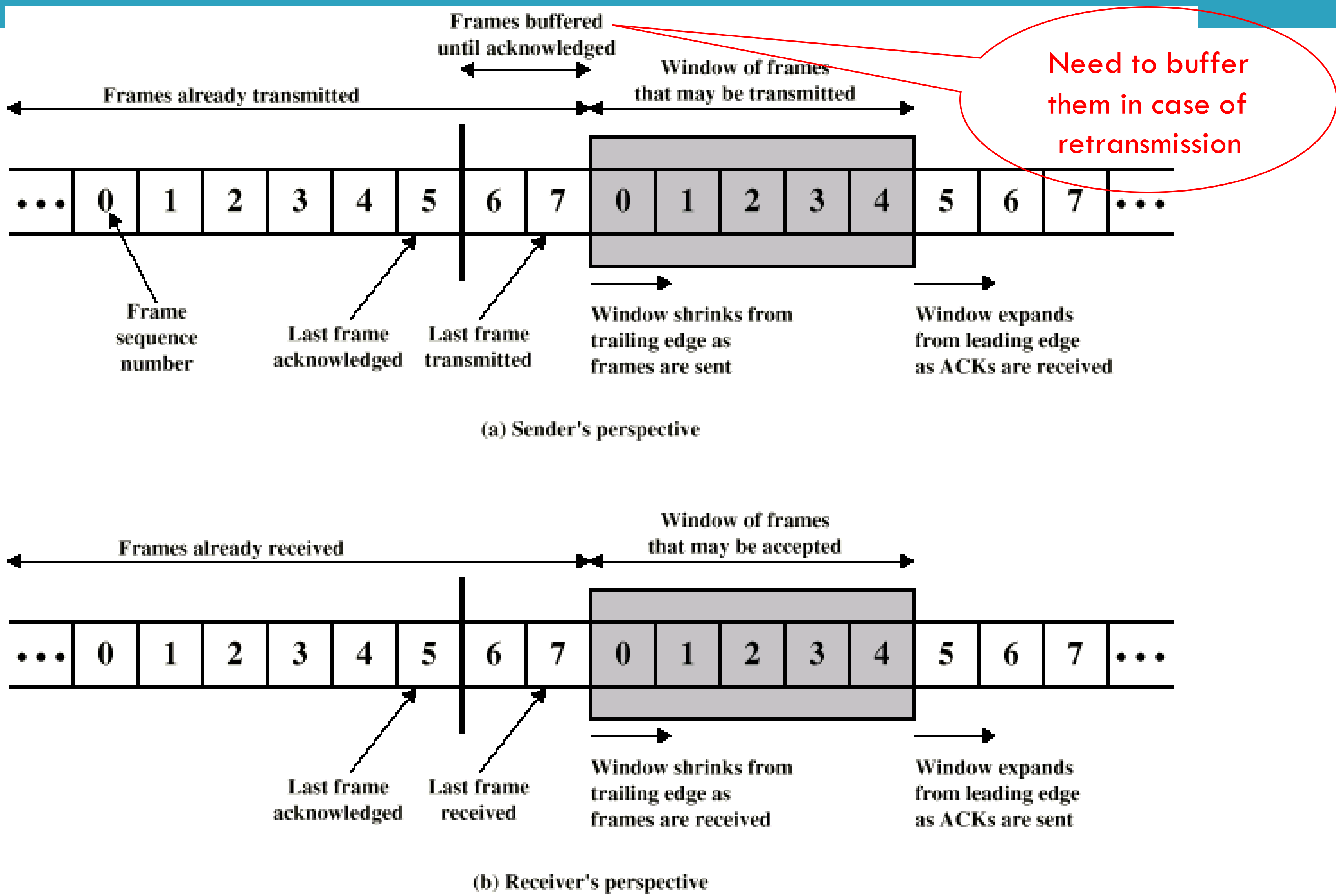
Sliding Window Protocols

- **At the sender**
  - Sending window
    - a set of sequence numbers corresponding to frames being under transmission (finite range of numbers)
- **At the receiver**
  - Receiving window
    - Sequence numbers for frames it is permitted to accept (finite range of numbers)

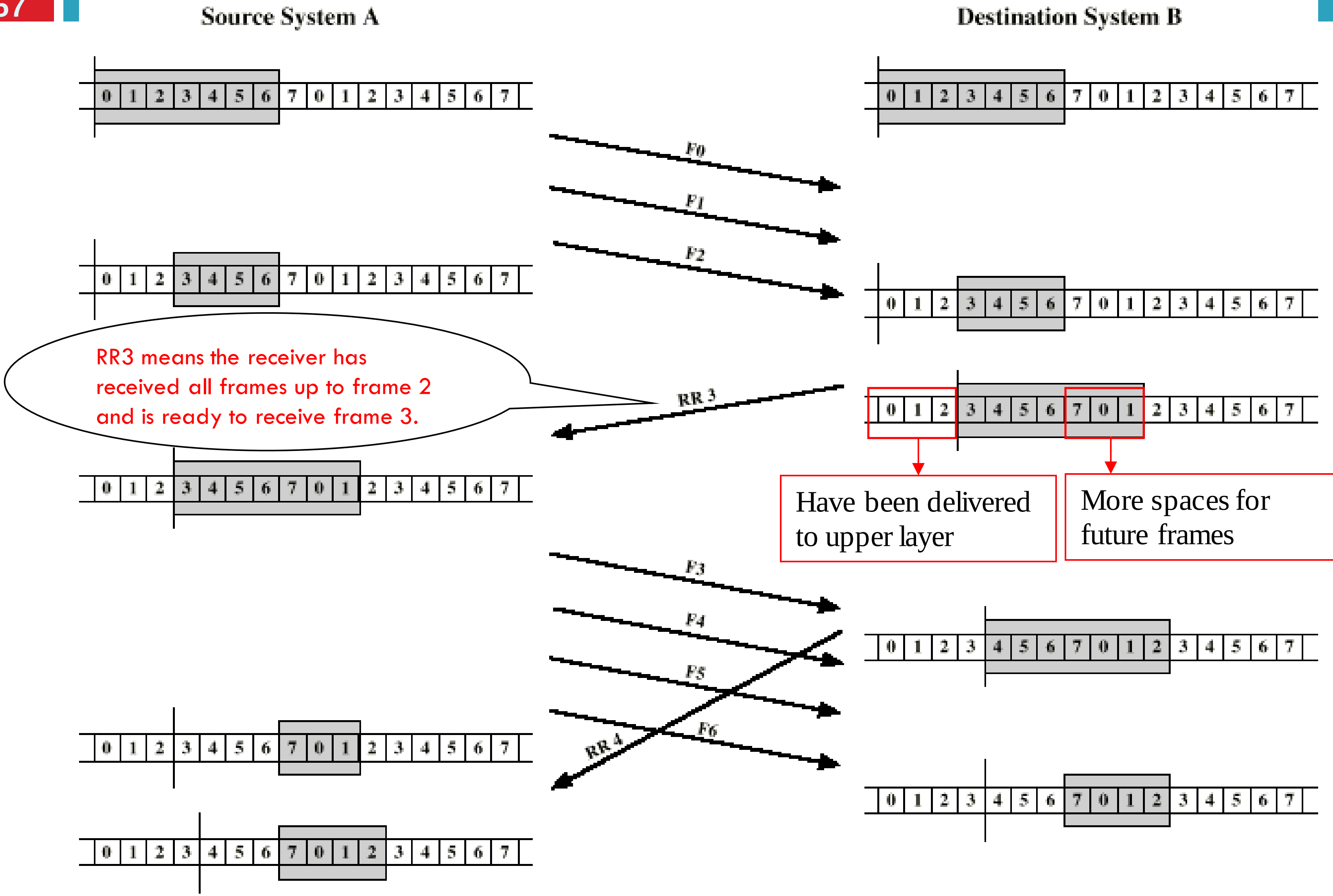
- The sender's and receiver's windows need
  - not have tha same lower and upper bounds and
  - even have the same size.

- The window size can be
  - fixed or
  - grow or shrink over the course of time as frames are sent and received

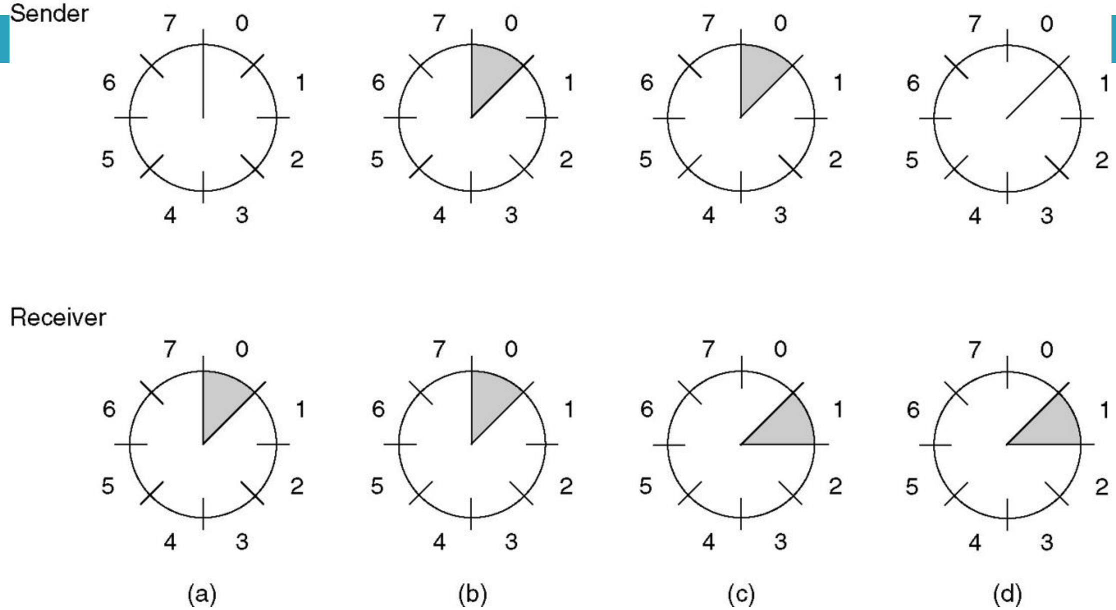
Sliding-Window Diagram



Example Sliding-Window



Sliding Window Protocols



A sliding window of size 1, with a 3-bit sequence number.

(a) Initially.

(b) After the first frame has been sent.

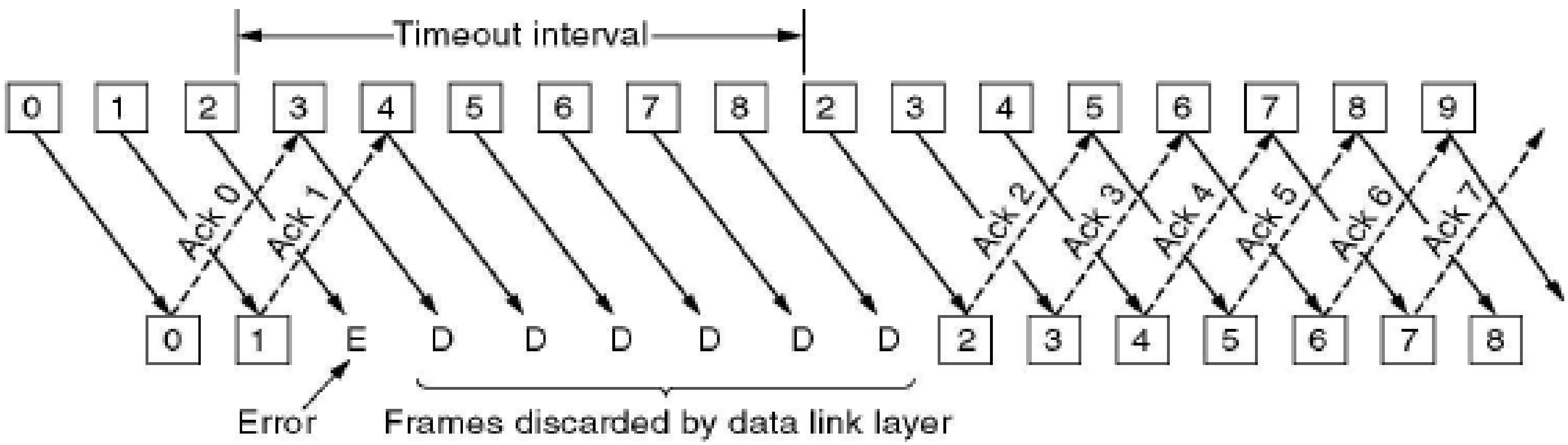
(c) After the first frame has been received.

(d) After the first acknowledgement has been received.

Go-Back-N

- A sliding window protocol where
  - the receiver's window size is fixed to 1,
  - while the sender has window size > 0.
- After receiving a damaged frame
  - Receiver discards all subsequent frames
  - Sender retransmits the damaged frame and all its successors after the times out

Go-Back-N

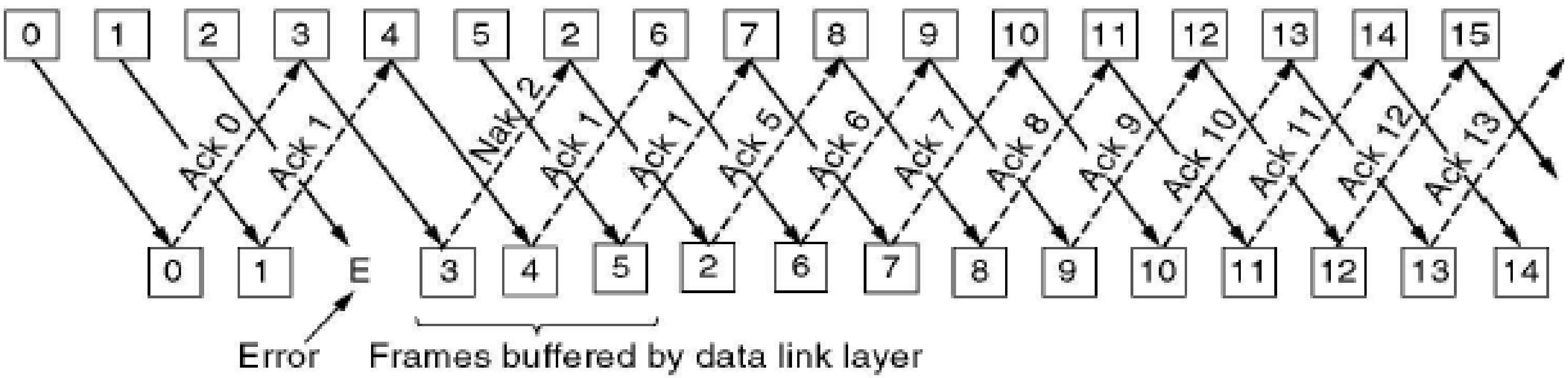


Timeout interval
0
1
2
3
4
5
6
7
8
2
3
4
5
6
7
8
9
Ack 0
Ack 1
Ack 2
Ack 3
Ack 4
Ack 5
Ack 6
Ack 7
0
1
E
D
D
D
D
D
D
2
3
4
5
6
7
8
Error
Frames discarded by data link layer

Selective Repeat

- Receiver’s window size is n (n >1)
  - At most n frames can be buffered
- Receiver stores all the correct frames following the bad one
- The sender retransmits only the bad frame not all its successors

Selective Repeat



Communication channels and piggybacking

- Simplex
  - Communication in one direction only
- Half-duplex
  - Communication in both directions, but only one direction at a time, not simultaneously.
- Full-duplex
  - Communication in both directions simultaneously

- The previous protocols assumed
  - a simplex channel to the upper (network) layer and
  - a (half-)duplex channel to the physical layer

- If we use duplex channel to the upper layers
  - Transmitting data packet and acknowledgements in both directions separately
  - Or using piggybacking
    - The header of a data packet sent in the opposite direction carries the acknowledgement back to the other side
    - widely applied in practice

Ethernet frame

<table>
<caption>802.3 Ethernet frame structure</caption>
<tr><th>Preamble</th><th>Start of frame delimiter</th><th>MAC destination</th><th>MAC source</th><th>802.1Q tag (optional)</th><th>Ethertype (Ethernet II) or length (IEEE 802.3)</th><th>Payload</th><th>Frame check sequence (32-bit CRC)</th><th>Interframe gap</th></tr>
<tr><td>7 octets</td><td>1 octet</td><td>6 octets</td><td>6 octets</td><td>(4 octets)</td><td>2 octets</td><td>42[note 2]–1500 octets</td><td>4 octets</td><td>12 octets</td></tr>
<tr><td colspan="2"></td><td colspan="6">64–1522 octets</td><td></td></tr>
<tr><td colspan="8">72–1530 octets</td><td></td></tr>
<tr><td colspan="9">84–1542 octets</td></tr>
</table>