Redes de Computadores

The Data Link Layer

Manuel P. Ricardo

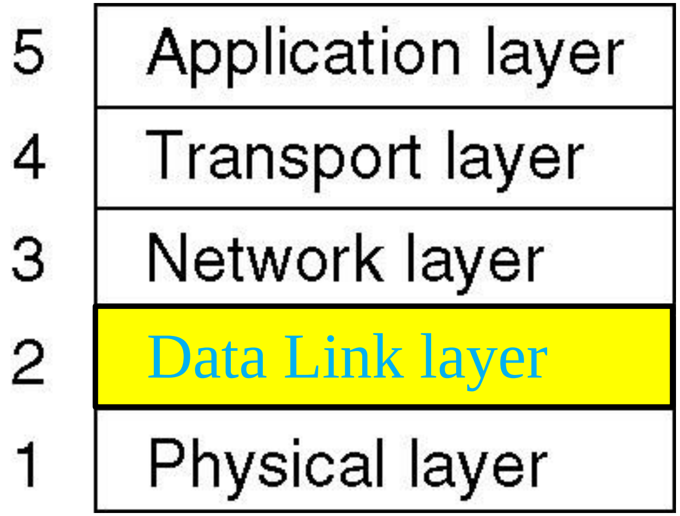
Faculdade de Engenharia da Universidade do Porto

- *What are the main services and functions of the Data Link layer?*
- *What is a frame? How to frame data? Why is stuffing important?*
- *What is the relationship between Bit Error Ratio and Frame Error Ratio?*
- *How to detect errors in a frame?*
- *How does Cyclic Redundancy Check operate?*
- *What are the CRC error detection capabilities?*
- *What is the purpose of Automatic Repeat ReQuest (ARQ)?*
- *What are the common ARQ mechanisms?*
- *How does Stop & Wait ARQ work?*
- *How does Go Back N ARQ ARQ work?*
- *How does the Selective Reject ARQ work?*
- *Why are sequence numbers important in ARQ mechanisms?*
- *What is the efficiency of the ARQ mechanisms?*
- *What mechanisms are employed in Ethernet, PPP and WLAN?*
- *What are the differences between End-to-End ARQ and Link-by-Link ARQ?*
- *Where are the ARQ mechanisms used in the TCP/IP reference model ?*

Data Link layer functions and services

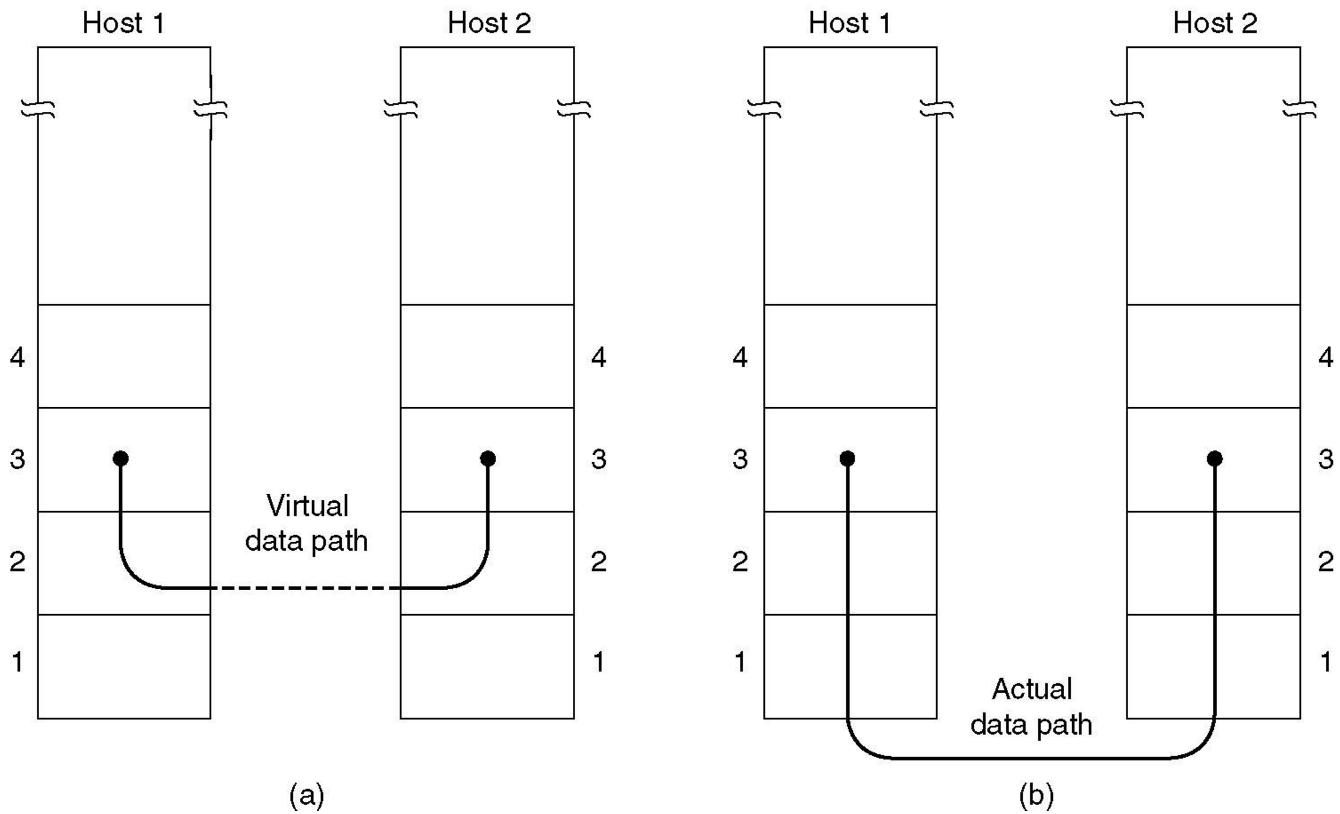
Data Link Layer – Functions and Services

- Main functions
  - » Eliminate/reduce transmission errors
  - » Regulate data flow
    - Slow receivers not swamped by fast senders
  - » Provide service to the network layer



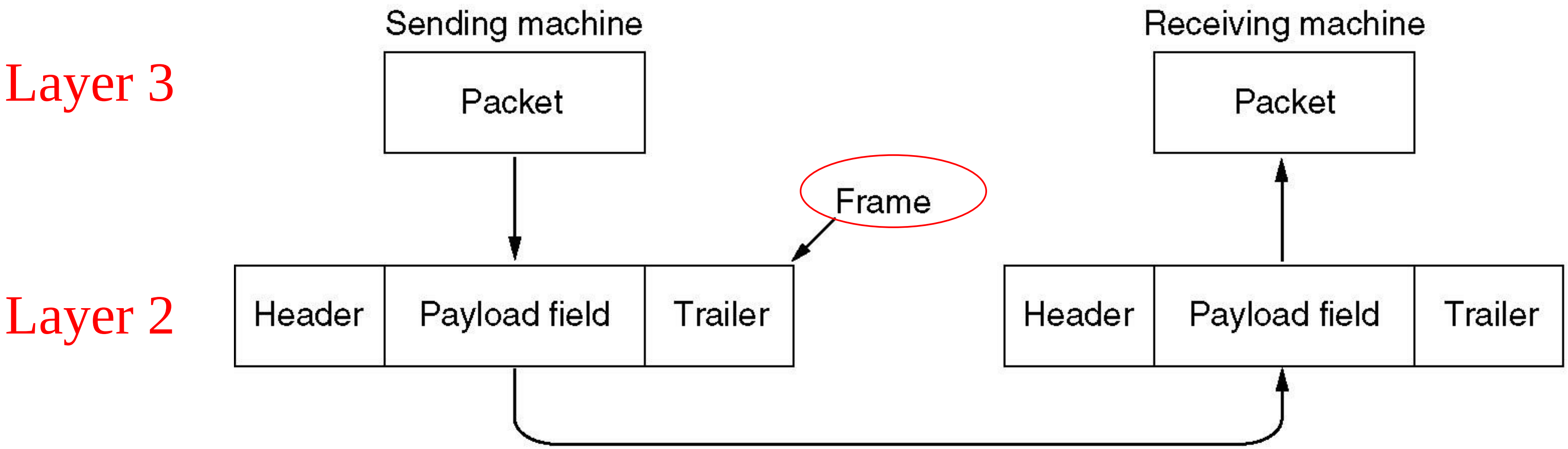
- Services provided
  - » Unacknowledged connectionless service
  - » Acknowledged connectionless service
  - » Acknowledged connection-oriented service

Services Provided to Network Layer

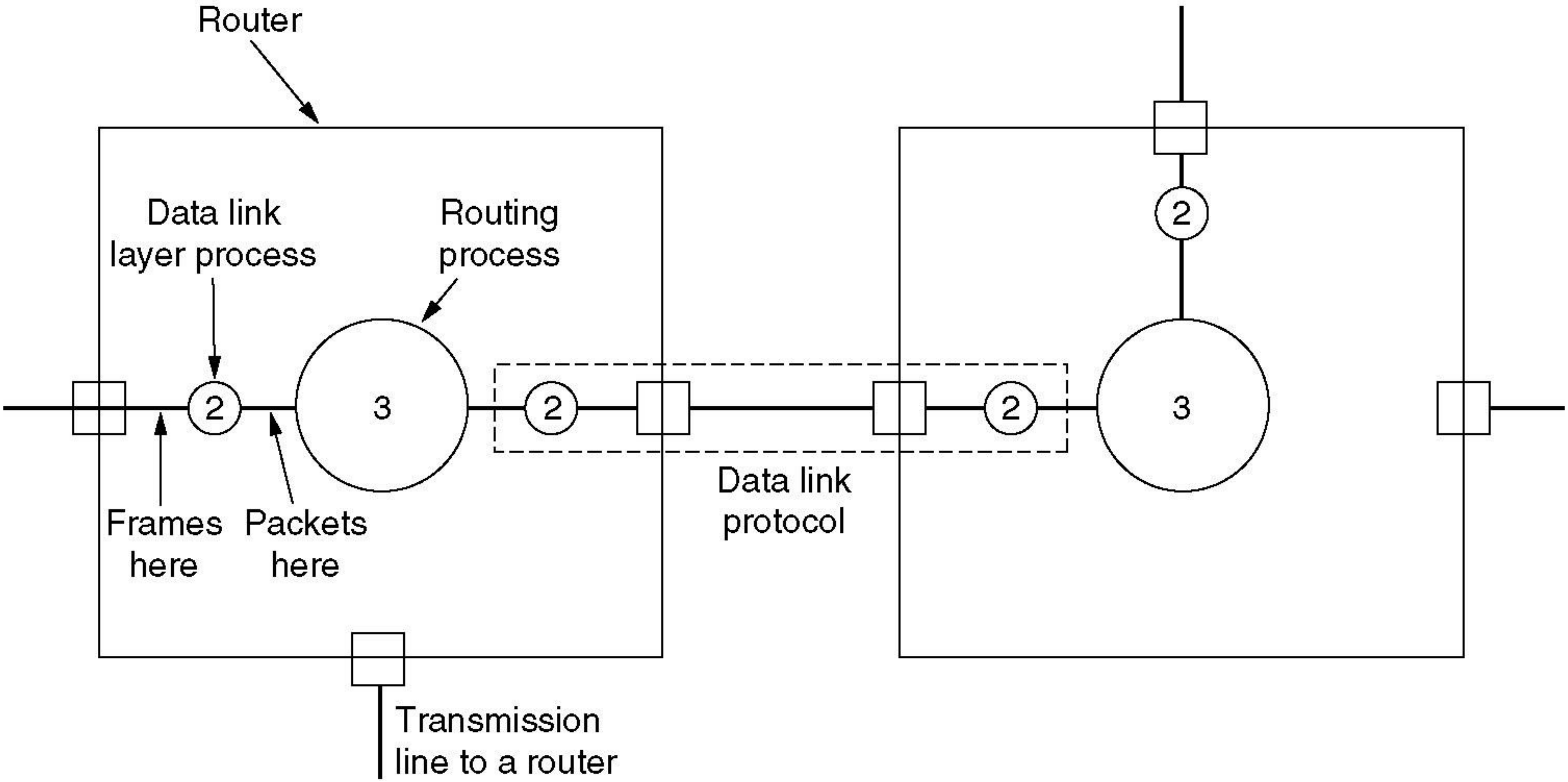


(a) Virtual communication (b) Actual communication

Layer 3 Packets and Layer 2 Frames



Placement of the Data Link Protocol



Framing

To Think

[Sender] → ..1001101101101101101110101.. → [Receiver]

Where is the data? Where does the frame start and stop?

How to split this bit stream into frames (sets of bits)?

Framing

- [Sender] → ..10011011011011011011110101.. → [Receiver]

  Where is the data? Where does the frame start and stop?

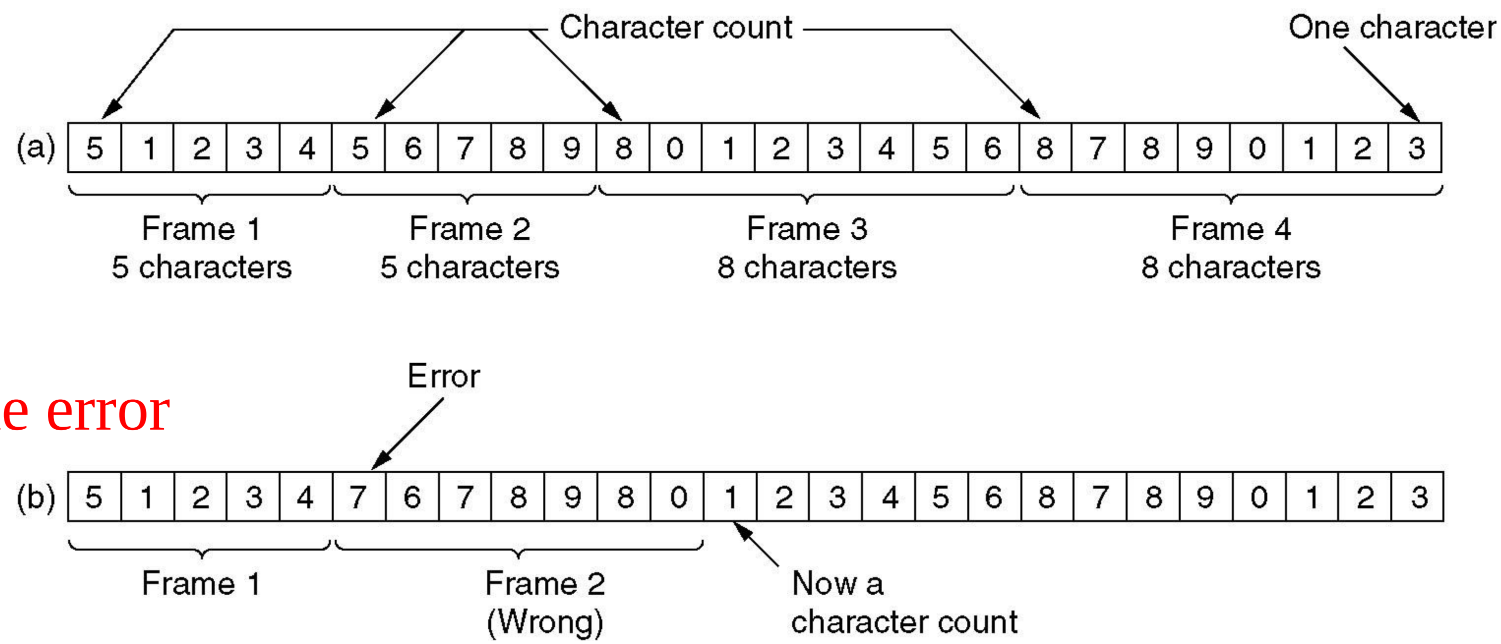
- Three methods
  - » **Character count**
  - » **Flag bytes with byte stuffing**
  - » **Start and ending flags, with bit stuffing**

Framing – Character count

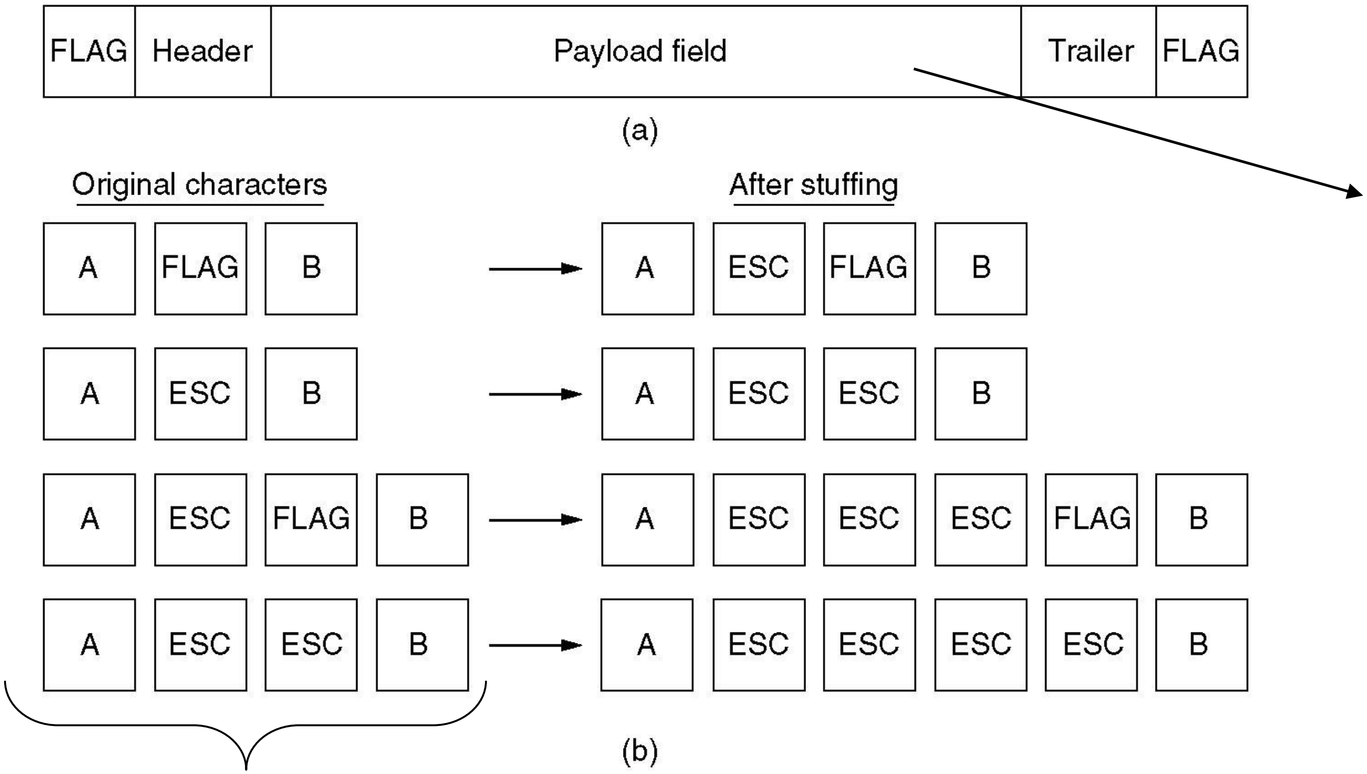
A stream of characters

(a) Without errors

(b) With one error



Framing - Flag bytes with byte stuffing



Problem if frame has internal character equal to FLAG!

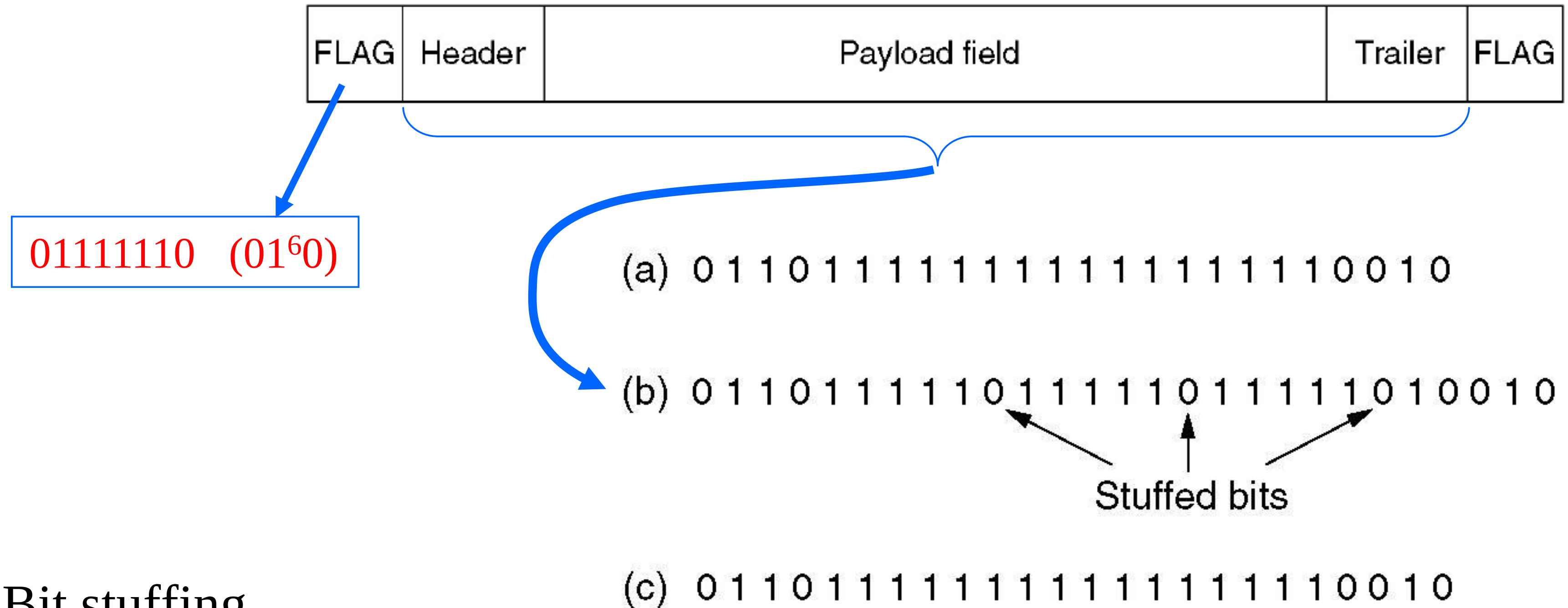
Problem solved by stuffing mechanism!

Data to be transported in the payload field

(a) A frame delimited by flag bytes

(b) Four examples of byte sequences before and after stuffing

Framing - Start and ending flags, with bit stuffing



Bit stuffing

(a) The original data

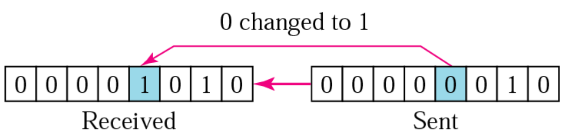
(b) The data as it appears on the line: 1^5 ➔ $1^5\underline{0}$

(c) The data as stored in receiver's memory **after destuffing: $\mathbf{0}1^5\underline{0}$** ➔ 01^5

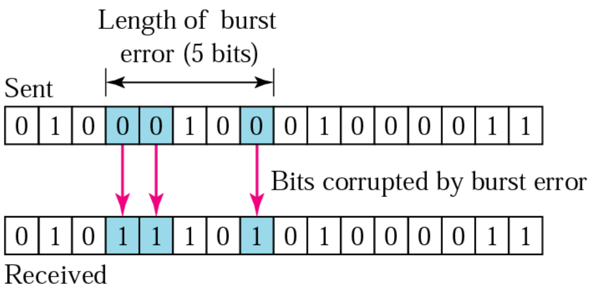
Error detection

Types of Errors

- Simple Error
  - Random and independent from previous error



- Errors in burst
  - Not independent; affect neighbour bits
  - Burst lenght defined by the first and last bits in error



To Think

- Assume
  - p – bit error probability (or Bit Error Ratio – BER)
  - n – frame length
  - Independent errors
  - FER: Frame Error Ratio

- Student A explains to Student B

  why $\boxed{\text{P[frame has no errors]} = (1-p)^n}$

- Student B explains to Student A

  why $\boxed{\text{P[frame has errors]} = 1-(1-p)^n \Leftrightarrow FER = 1-(1-BER)^n}$

Counting Errors

- Assume
  - p – bit error probability (or Bit Error Ratio – BER)
  - n – frame length
  - Independent errors

$$FER = 1-(1-BER)^n$$

- P[frame has no errors]= $(1-p)^n$

  the n bits are good!

- P[frame has errors]= $1-(1-p)^n$

  P[frame has errors]= Frame Error Ratio (FER)

- P[1 bit received in error]= $\binom{n}{1} p(1-p)^{n-1}$
- P[i bits received in error]= $\binom{n}{i} p^i (1-p)^{n-i}$

$p=10^{-7}$ (**good wired channel**)

$n=10^4$ (~ Ethernet frame length)

$FER = 1-(1-10^{-7})^{10^4} \approx 10^{-3}$

$p=10^{-3}$ (**wireless channel**)

$n=10^4$ (~ Ethernet frame length)

$FER = 1-(1-10^{-3})^{10^4} \approx 1$

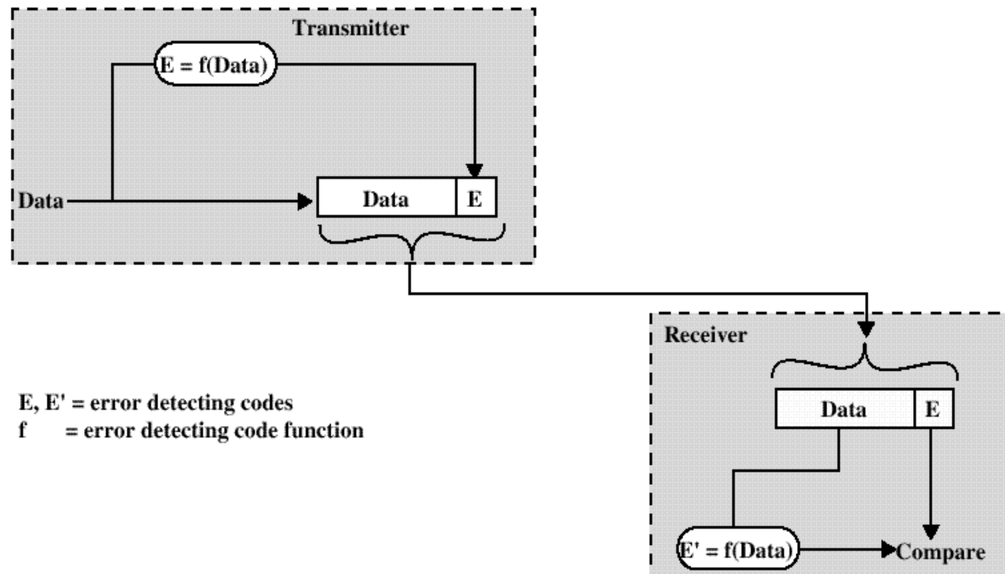
Error Techniques

- Error techniques required!
  - » Detection (and correction)

- Effectiveness of error detection technique (code) characterized by
  - » Minimum distance of code: d
    - – min number of bit errors undetected in a block of n bits
    - – if fewer than d errors occur, errors are detected
  - » Burst detecting ability: B
    - – max burst length of errors detected

Error Detection Techniques

- Used by the receiver to determine if a packet contains errors
  - If a packet is found to contain errors,
    the receiver may request the transmitter to re-send the packet



- Introducing redundancy ➔
  - k ➔ k+r

    k: data bits; r: redundancy bits

- Error detection techniques
  - Parity check
  - Cyclic Redundancy Check (CRC)
  - …

Simple Parity Check

- One parity bit added to every k information bits so that
  - » The total number of bits 1 even ➔ even parity

    1110111 1101110 1010110 1101100 1100100

    11101110 11011101 10101100 11011000 11001001
  - » The total number of bit 1 is odd ➔ odd parity

- Detection of
  - » simple errors
  - » any number of odd errors in a block of k+1 bits

- Undetected
  - » Even number of errors in a block

    n=k+1, block size

    p: bit error probability

$$P(undetected) = \sum_{i \ even} \binom{n}{i} p^i (1-p)^{n-i}$$

- Used in Character Oriented protocols

Bi-dimensional Parity

- Blocks represented in rows
  - » Parity bit per row; parity bit per column

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

Horizontal checks

Vertical checks

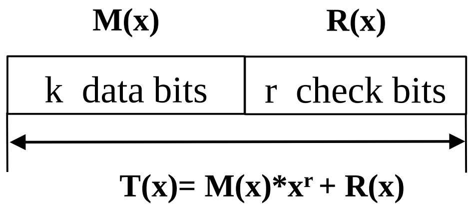
1	0	0	1	0	1	0	1
0	1	1	1	0	1	0	0
1	1	1	0	0	0	1	0
1	0	0	0	1	1	1	0
0	0	1	1	0	0	1	1
1	0	1	1	1	1	1	0

- Minimum code distance d=4

  Any four errors in a rectangular configuration becomes undetectable

Cyclic Redundancy Check (CRC)

- Bit string represented as a polynomium
  - » 110011 → x^5+x^4+x+1
- Module 2 operations
  - » Additions and subtractions identical to exclusive OR
  - » no carry, no borrow
- M(x); R(x); $T(x)=M(x) * x^r + R(x)$



- How to compute the check bits: R(x)?
  - » Choose a generator string G(x) of length r+1 bits
  - » Choose R(x) such that T(x) is a multiple of G(x): $T(x)=A*G(x)$
- $T(x)=M(x)x^r+R(x) = A*G(x)$ ⇔

  $M(x)x^r = A*G(x) + R(x)$ (mod 2 arithmetic)

  → $R(x)$ = remainder of $M(x)x^r / G(x)$
- Choice of G(x) is very important! ($G(x)=x^r+\ldots+1$)

CRC - Generating R(x)

- $r=3$, $x^r=x^3$; $G(x)=x^3+1$ (1001)
- $M(x)=x^5+x^4+x^2+1$ (110101)
- $M(x)^* \, x^3 =$ $x^8+x^7+x^5+x^3$ (110101000)
- $R(x)=$ remainder of $M(x)x^r$ / $G(x)$
- $R(x)=x+1$ (011)

M(x)* x^3 | G(x)

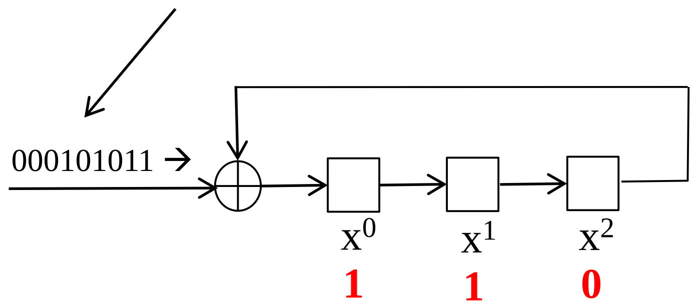
1	**1**	**0**	**1**	**0**	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**1**		
1	0	0	1						1	1	0	0	1	1
0	1	0	0	0										
	1	0	0	1										
	0	0	0	1	1									
		0	0	0	0									
		0	0	1	1	0								
			0	0	0	0								
			0	1	1	0	0							
				1	0	0	1							
				0	1	0	1	0						
					1	0	0	1						
					0	**0**	**1**	**1**	$\boxed{R(x)}$					

- Sent word
  - » $T(x)=M(x) * x^r+ R(x) = x^8+x^7+x^5+x^3+x+1=$ 110101 011

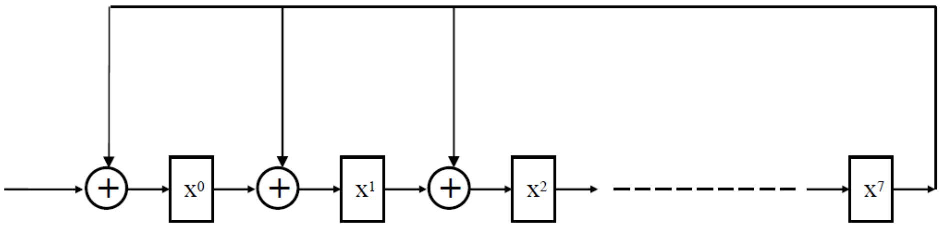
CRC - Generating R(x) with a Shift Register

- R(x) easily generated in hardware

- $G(x)=x^3+1$
  - » $M(x)*\ x^3 = x^8+x^7+x^5+x^3$ (110101000)
  - » $R(x)=x+1$ (011)



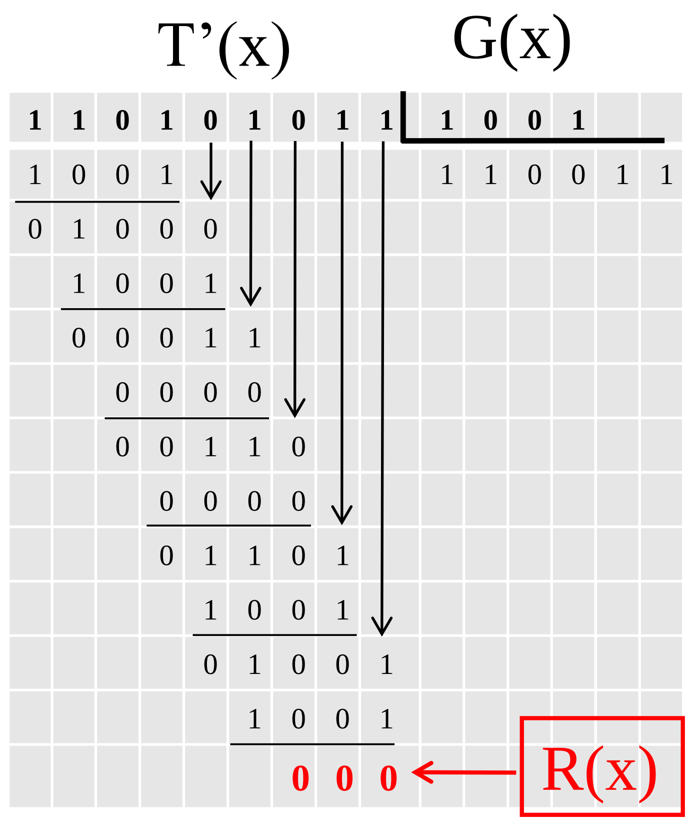
- $G(x)=x^8+x^2+x+1$



CRC – Checking at the Receiver

- Let T’(x) be the received word
  - » T’(x)= $x^8+x^7+x^5+x^3+x+1$ (110101 011)
- Divide T’(x) by G(x)
  - » If remainder R(x)=0 ➔ no errors
  - » If remainder R(x) !=0

    ➔ errors have occurred



CRC - Performance

- For r check bits per frame the following can be detected
  - All patterns of 1, 2, or 3 errors ($d > 3$)
  - All bursts of errors of **r** or fewer bits
  - All errors consisting of an odd number of inverted bits

- Common polynomials
  - ITU-16: r=16, $G(x) = x^{16} + x^{12} + x^5 +1$ (10001000000100001)
  - ITU-32: r=32,

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

Automatic Repeat reQuest (ARQ)

Automatic Repeat ReQuest (ARQ)

- When the receiver detects errors in a frame

  how to ask the sender to retransmit the frame?

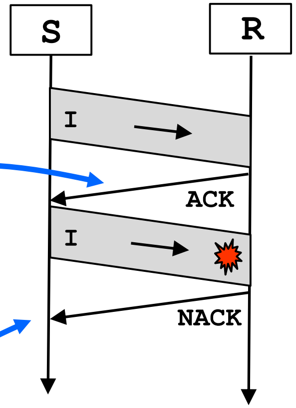
- ARQ mechanisms

  Mechanisms that automatically request the retransmission of
    - missing packets
    - packets with errors

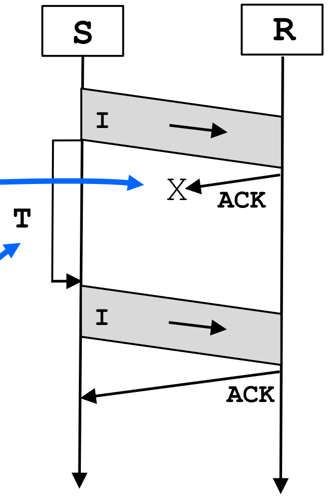
- Three common ARQ schemes
  - » **Stop and Wait**
  - » **Go Back N**
  - » **Selective Repeat**

Stop and Wait ARQ

- Sender
  - » transmits Information frame **I**
    waits for positive confirmation **ACK** from receiver
- Receiver: receives **I** frame
  - » If **I** frame has no error ➔ confirms with **ACK**
  - » If **I** frame has error ➔ sends **NACK**

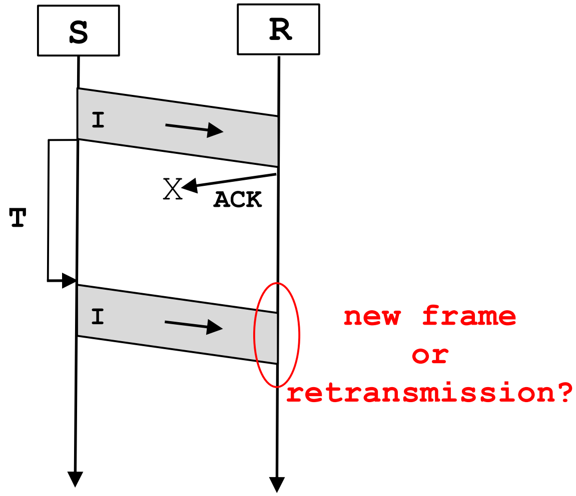


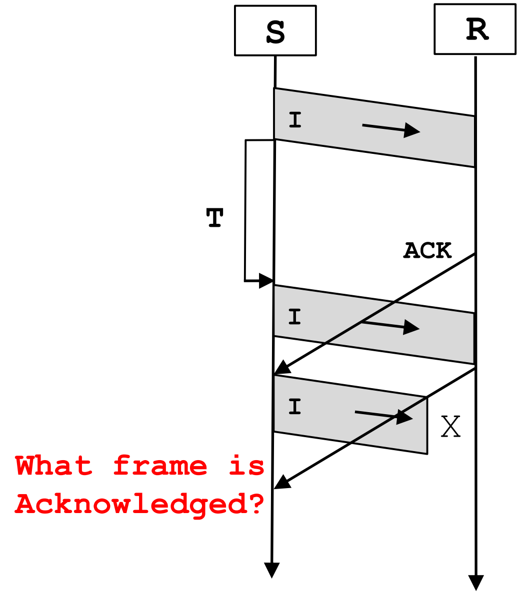
- Sender
  - » Receives **ACK** ➔ proceeds and transmits new frame
  - » Receives **NACK** ➔ retransmits frame **I**



- Problem
  - » What happens if **I, ACK** or **NACK** is lost?
    ➔ Timeout required!

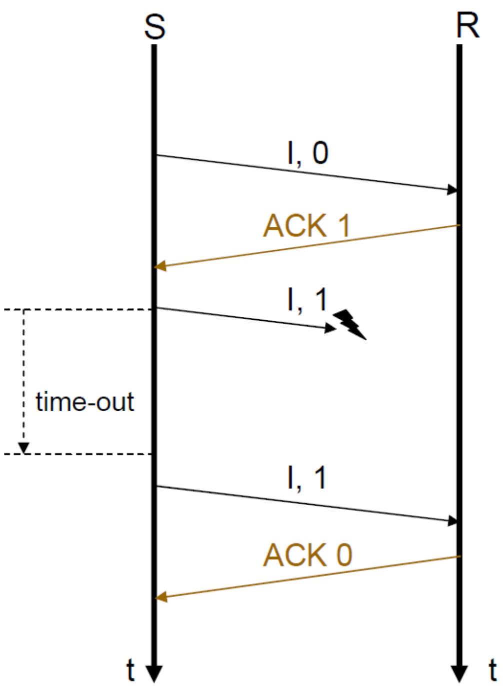
Stop and Wait ARQ – Sequence Numbers Required

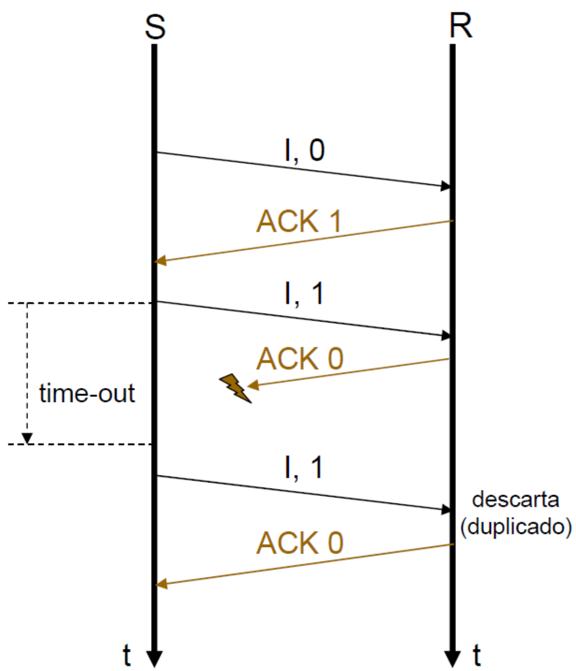


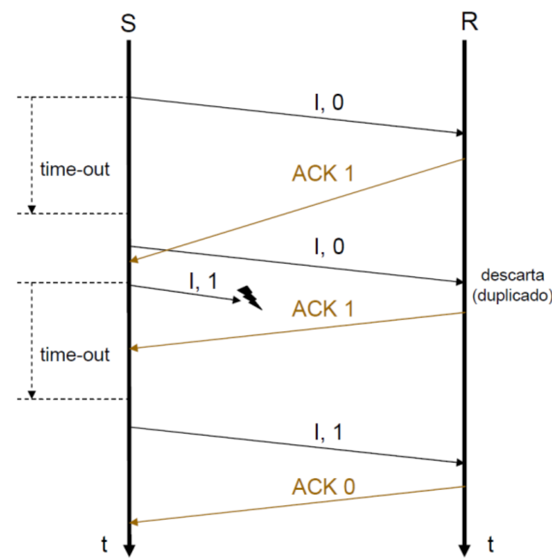


- Solution
  - **I** frames numbered: **I(0)**, **I(1)**
  - **ACK** frames numbered: **ACK(0), ACK(1)**
  - **ACK(i)** indicates that receiver is waiting for frame **I(i)**
  - No **NACK** required
  - Module 2 numbers

Stop and Wait ARQ – Examples

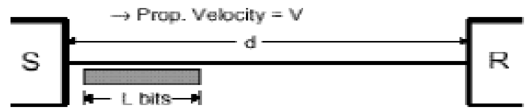






Stop and Wait – Efficiency Example

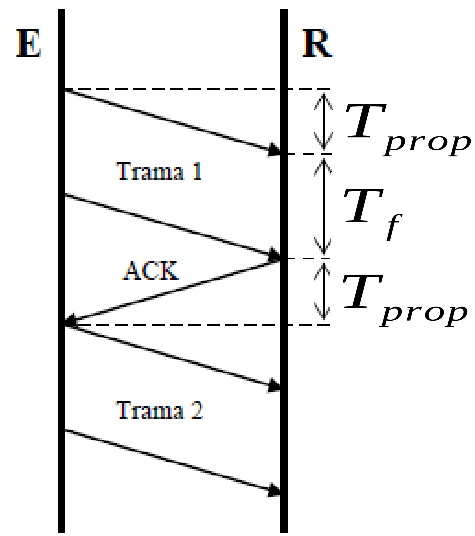
- WAN ATM
  - d = 1000 km
  - L = 424 bit, R = 155.52 Mbit/s
  - T_t = 2.7 µs
  - Fibra óptica → 5 µs/km → τ = 5 ms
  - a = 1852
  - **S = 1 / 3705 = 0.0003**
- LAN
  - d = 0.1 ~ 10 km
  - L = 1000 bit, R = 10 Mbit/s
  - T_t = 100 µs
  - Cabo coaxial → 4 µs/km → τ = 0.4 ~ 40 µs
  - a = 0.004 ~ 0.4
  - **S = 0.55 ~ 0.99** (e se R = 100 Mbit/s?)
- Modem sobre linha telefónica
  - d = 1000 m
  - L = 1000 bit, R = 28.8 kbit/s
  - T_t = 34.7 ms
  - UTP → 5 µs/km → τ = 5 µs
  - a = 1.44×10^{-4}
  - **S ≃ 1.0**



→ R – *data rate* (bit/s)

$$T_f = \frac{L}{R} = T_t$$

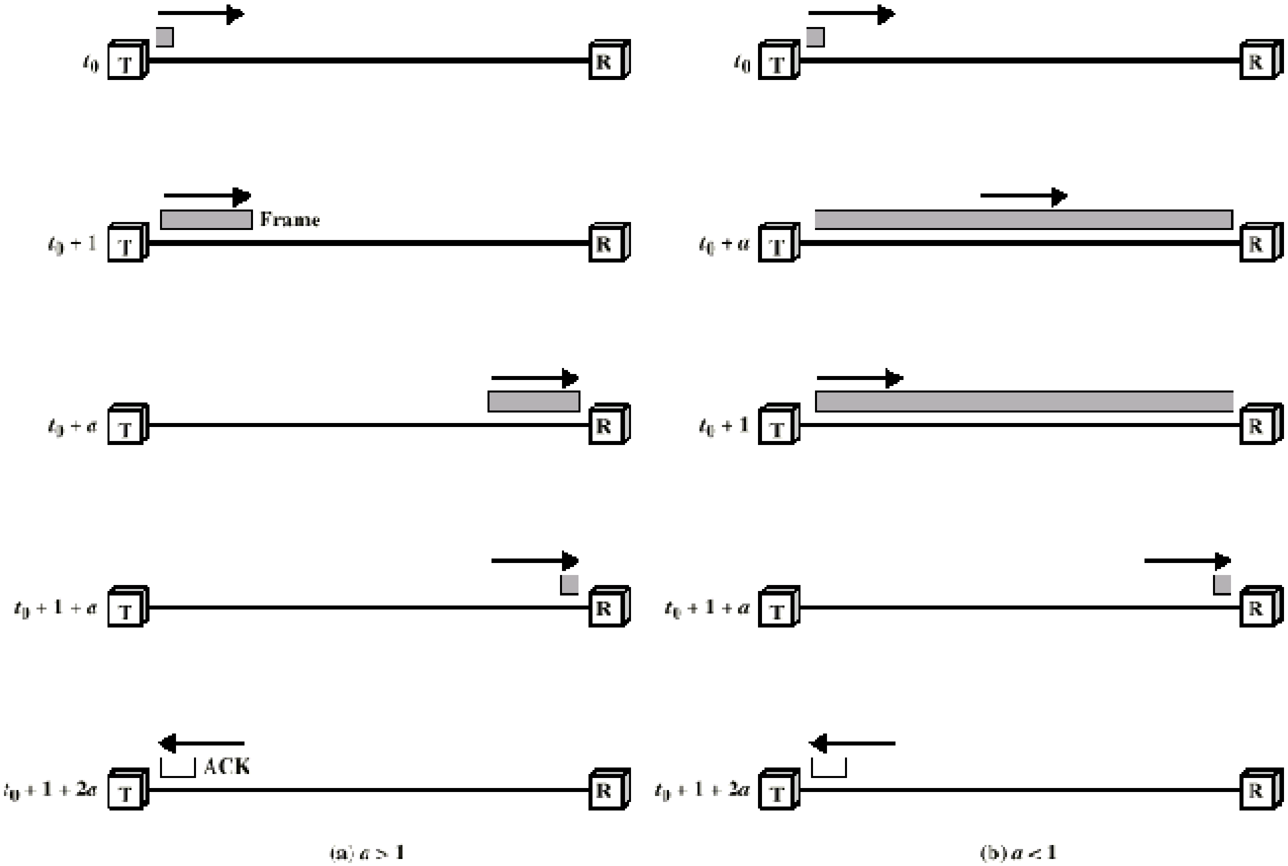
$$T_{prop} = \frac{d}{V} = \tau$$



$$a = \frac{T_{prop}}{T_f}$$

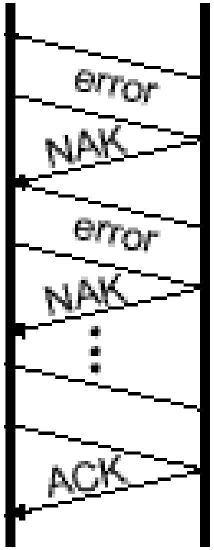
$$S = \frac{T_f}{T_{prop} + T_f + T_{prop}} = \frac{1}{1 + 2a}$$

Stop and Wait - Efficiency



Stop-and-Wait Link Utilization (transmission time = 1; propagation time = a)

Stop and Wait ARQ – Efficiency with Errors



- p_e – frame error probability
- P[A=k]
  - Probability of **k Attempts** required to transmit a frame with success

$$\mathrm{P}\left[A=k\right]=p_e^{\,k-1}(1-p_e)$$

- E[A]

  expected number of Attempts

  to transmit a frame with success

$$E[A]=\sum_{k=1}^{+\infty}k*\mathrm{P}[A=k]=\frac{1}{1-p_e}$$

- Efficiency

$$S=\frac{T_f}{E[A](T_f+2T_{prop})}=\frac{1}{E[A](1+2a)}=\frac{1-p_e}{1+2a}$$

To Think

- Assume Sender and Receiver are separated by a large distance?

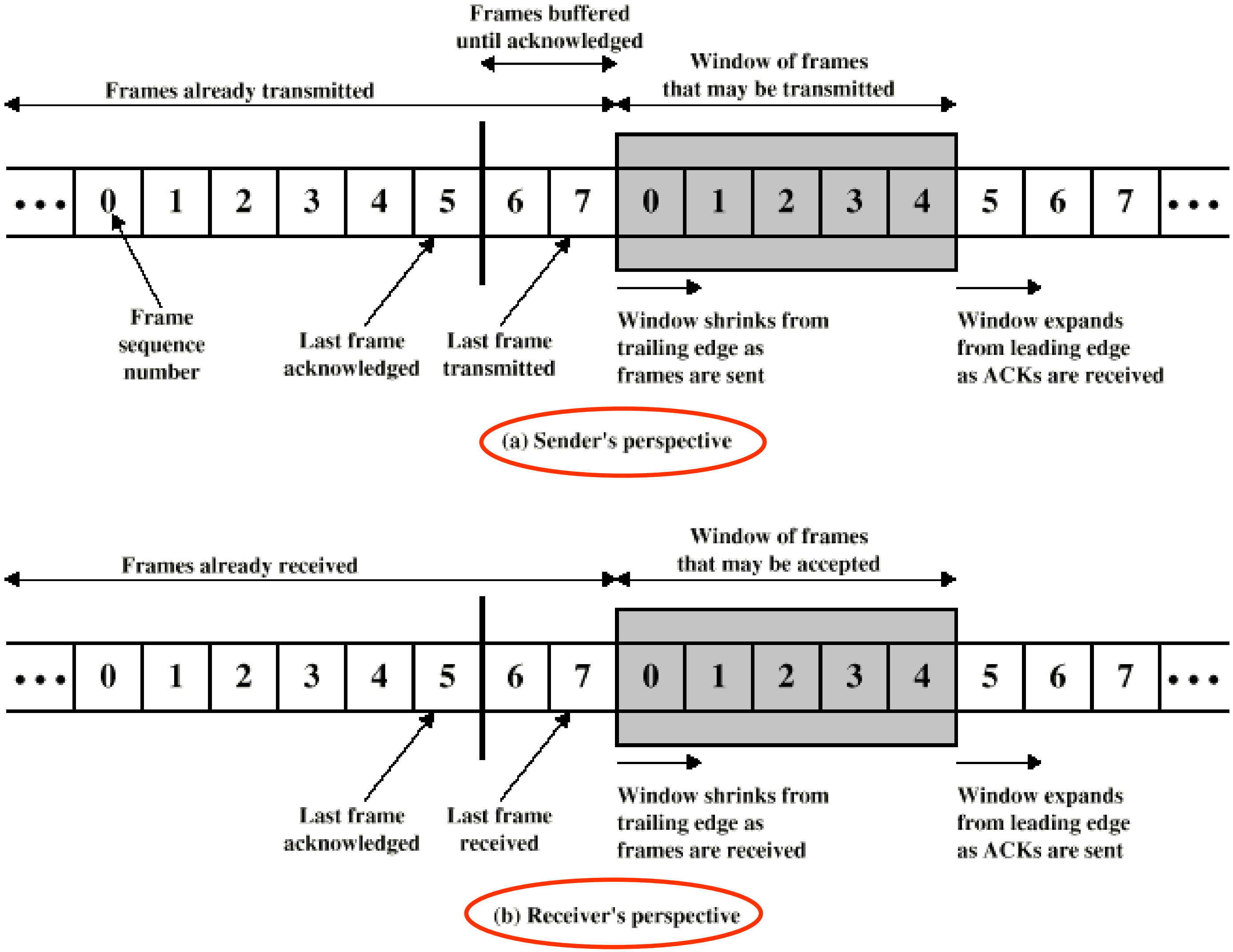
  How to improve the Efficiency of the Stop &Wait ARQ?

Go Back N ARQ (Sliding Window)

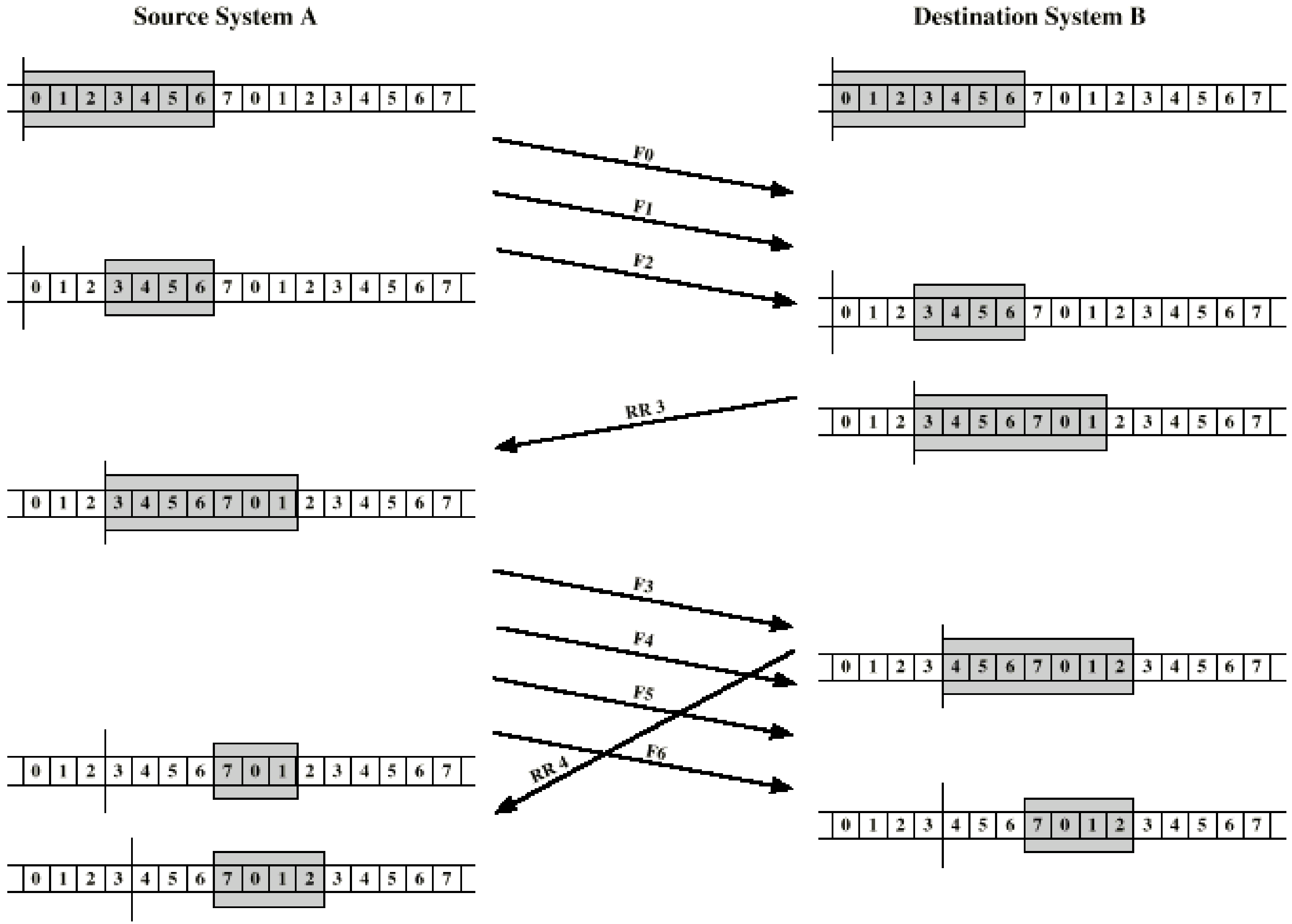
- Stop and Wait
  - » inefficient when $T_{prop} > T_f$ ($a > 1$)
  - » sends only one frame per Round-Trip Time ($RTT=2*T_{prop} + T_f$)

- Go Back N
  - » allows transmission of new packets before earlier ones are acknowledged
  - » uses a Sliding Window mechanism
    - – sender can send packets that are within a "window" (range) of packets
    - – window advances as acknowledgements for earlier packets are received

Sliding Window - Model



Sliding Window - Example



Go Back N ARQ – Basic Behaviour

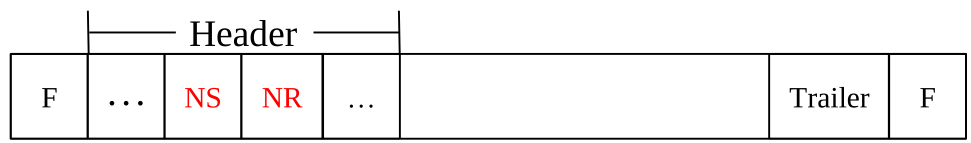
- Sender
  - » may transmit up to **W** frames without receiving RR
    RR - Receiver Ready = ACK
  - » I frames are numbered sequentially I(NS): I(0), I(1), I(2), …
  - » Cannot send I(NS=i+W) until it has received the RR(NR=i)

- Receiver
  - » does not accept frames out of sequence
  - » sends RR(NR) to sender indicating
    - – that **all the packets up to NR-1 have been received in sequence**
    - – the sequence number, NR, of the next expected frame

Go Back N ARQ – Maximum Window, Extensions

- Sequence numbers are represented module M
  - » NS, NR in {0, 1, …, M-1}

- Maximum Window
  - » W = M-1= 2^k -1
  - » k is number of bits used to code sequence numbers



- Extensions to basic behaviour
  - » Piggybacking can be used for bidirectional flows
  - » RR information can be sent in the data packets of opposite direction

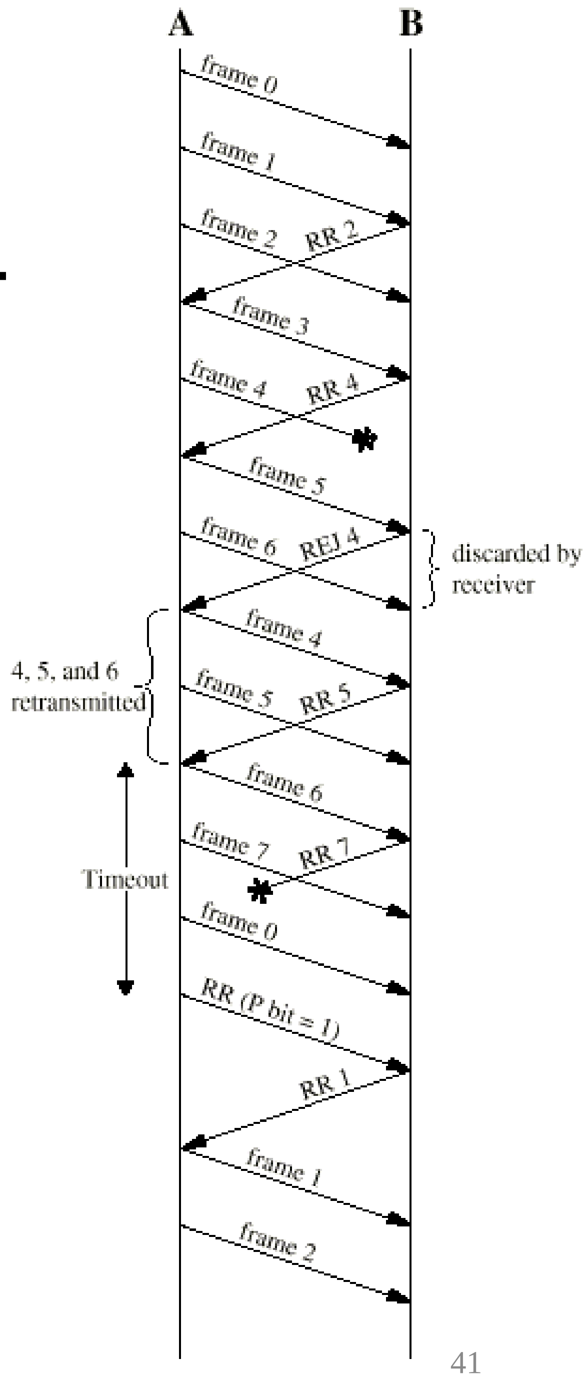
Go Back N ARQ – Behaviour under Errors

- Frame with errors
  is silently discard by the Receiver

- If Receiver receives Data frame out of sequence
  - » First out-of-sequence-frame?
    - – Receiver sends REJ(NR)
    - – NR indicates the next in-sequence frame expected
  - » Following out-of sequence-frames
    - – Receiver discards them; no REJ sent

- When Sender receives REJ(NR=x), the Sender
  - » Goes-Back and retransmits I(x), I(x+1), …
  - » Continues using Sliding Window mechanism

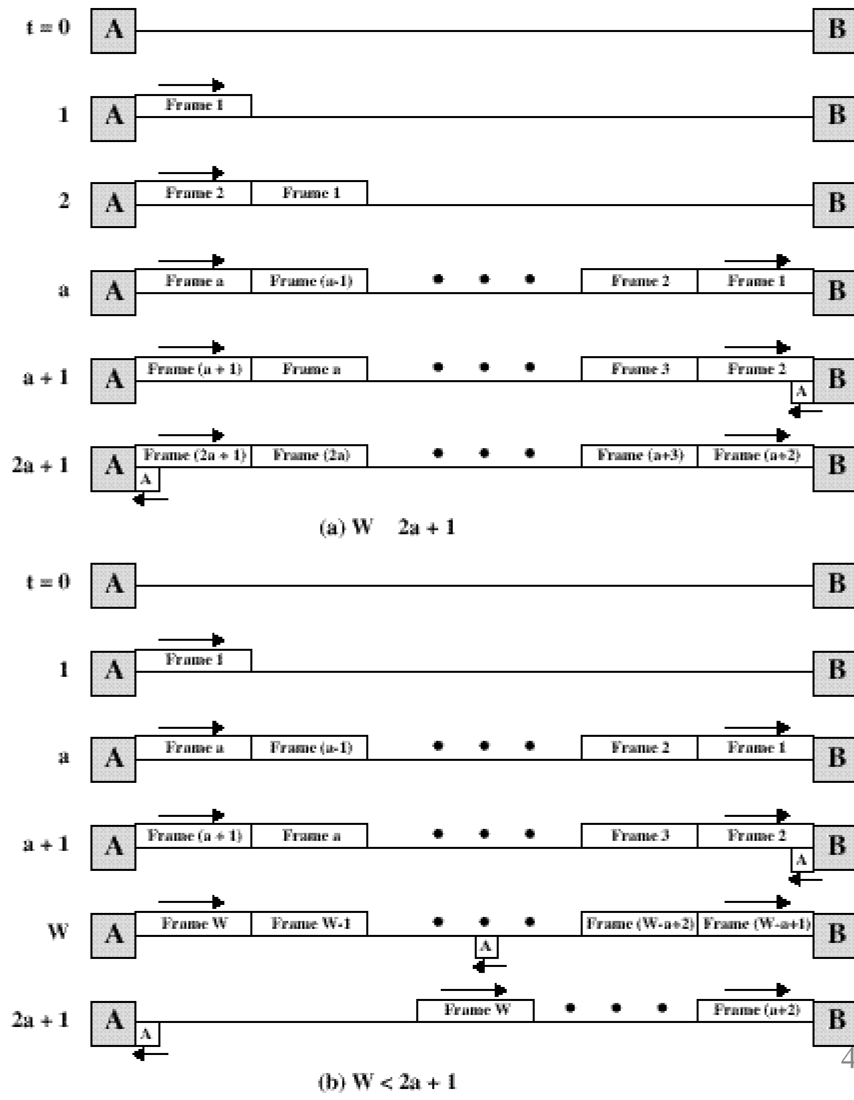
- If timeout occurs, the Sender
  - » requests the Receiver to send a RR message
  - » by sending a special message (RR command message)



Go Back N – Efficiency

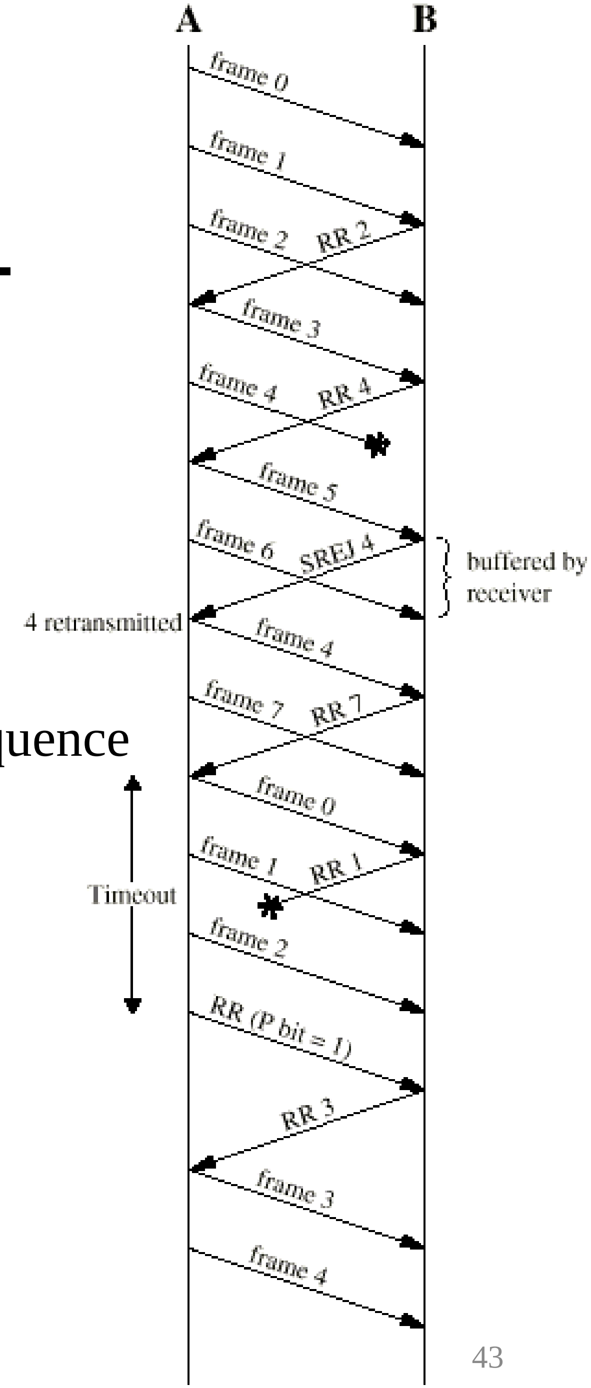
- If W ≥ 1+2a ➔ S = 1

- If W < 1+2a ➔ S = W/(1+2a)



Selective Repeat ARQ

- Uses Sliding Window, but …
- Receiver
  - » accepts out-of-sequence-frames
  - » confirms negatively, SREJ, a frame not arrived
  - » uses RR to confirm blocks of frames arrived in sequence
- Sender
  - » retransmits only the frames signaled by SREJ
- Adequate if W (a) is very large
- Maximum window size, $W = \dfrac{M}{2} = 2^{k-1}$

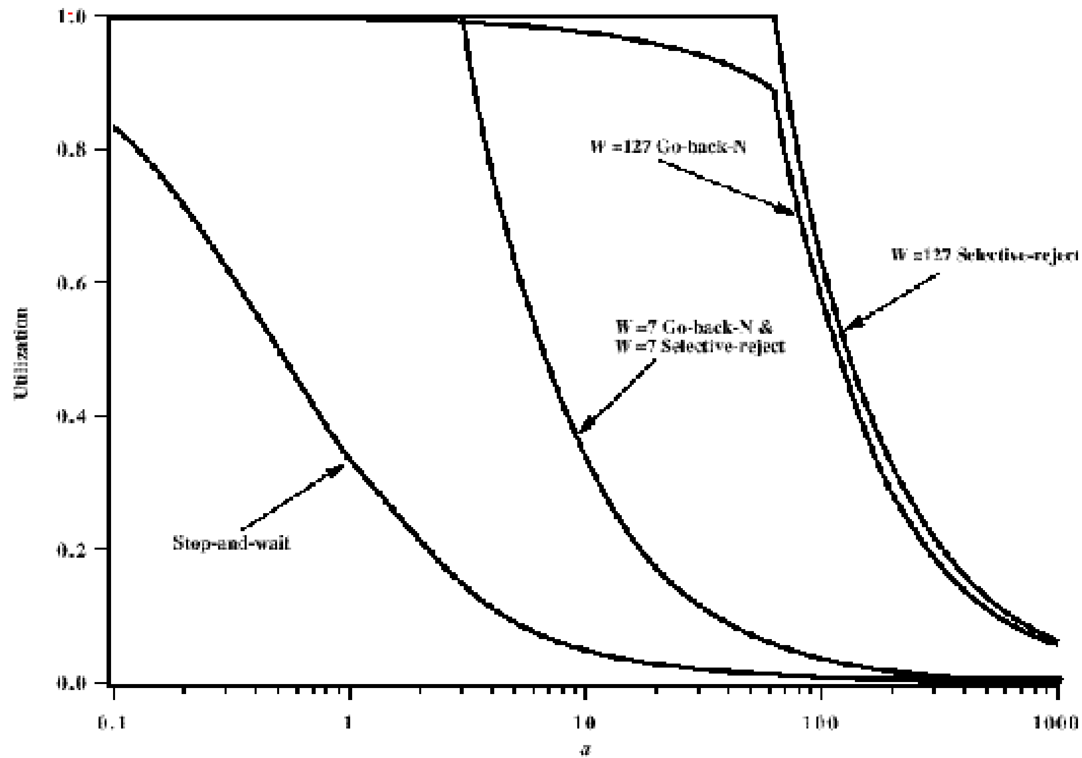


Go-Back-N and Selective Repeat ARQ – Efficiency under Errors

- *Go-Back-N ARQ*

  p_e – frame error probability (= FER)

$$S = \begin{cases} \dfrac{1-p_e}{1+2ap_e} & ,W \geq 1+2a \\ \dfrac{W(1-p_e)}{(1+2a)(1-p_e+Wp_e)} & ,W < 1+2a \end{cases}$$



ARQ Utilization as a Function of a ($P = 10^{-3}$)

- *Selective Repeat ARQ*

$$S = \begin{cases} 1-p_e & ,W \geq 1+2a \\ \dfrac{W(1-p_e)}{1+2a} & ,W < 1+2a \end{cases}$$

Framing, Error detection and ARQ in common networks

Ethernet

- Framing
  - » Start of frame: preamble + SFD
  - » End of frame: end of signal transitions (Manchester code), length

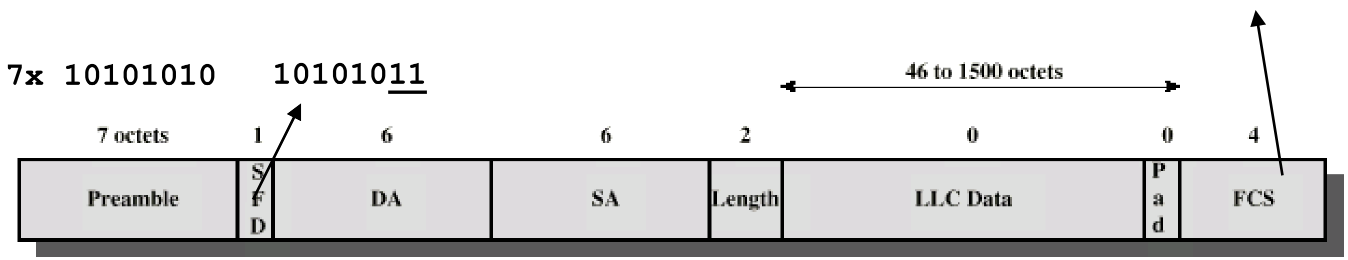
- Error detection: FCS → ITU-32, G(x) =x^{32}+ …+1

- No ARQ
  - » Bit Error ratio (BER) very low
    ➔ Frame Error Ratio (FER) low
  - » CRC/FCS strong
    - – Good detection of error frames
    - – Frame detected with errors ➔ discarded

$p=10^{-7}$ (**good wired channel**)
$n=10^4$ (~ Ethernet frame length)

P[frame has errors]= $1-(1-10^{-7})^{10^4} \approx 10^{-3}$

ITU-32: r=32, G(x) =x^{32}+ …+1



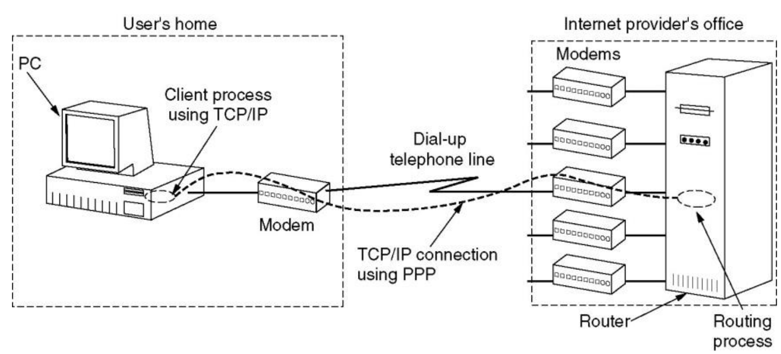
SFD = Start of frame delimiter
DA = Destination address
SA = Source address
FCS = Frame check sequence

Point to Point Protocol

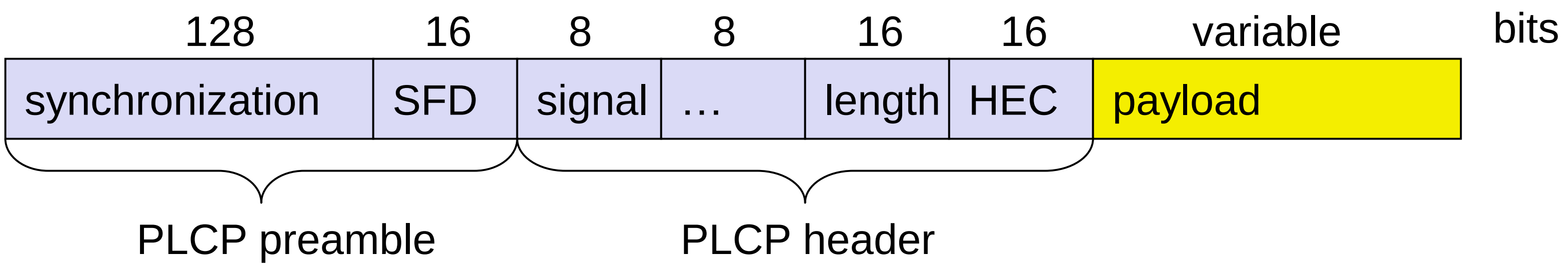
Bytes	1	1	1	1 or 2	Variable	2 or 4	1
	Flag 01111110	Address 11111111	Control 00000011	Protocol	Payload	Checksum	Flag 01111110

Byte stuffing

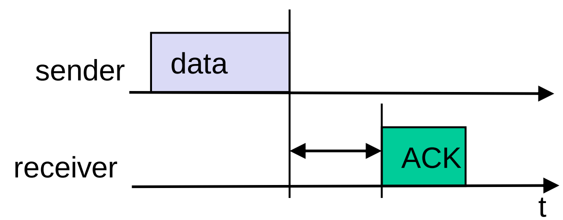
- Framing: Flags - 0x7E
- Byte stuffing: ESC – 0x7D
- Error detection – can be negotiated
- No ARQ



Wireless LAN



- Framing
  - » Synchronization: 0101010 …
  - » SFD (Start Frame Delimiter → 1111001110100000
  - » Length → Payload length **<u>in us</u>**
- HEC (Header Error Check)
  - » ITU-16, G(x)= $x^{16}+x^{12}+x^5+1$
- Payload (data)
  - » Protected by strong codes
- ARQ
  - » modified version of Stop and Wait



- Signal: Payload bitrate (0A: 1 Mbit/s DBPSK; 14: 2 Mbit/s DQPSK)

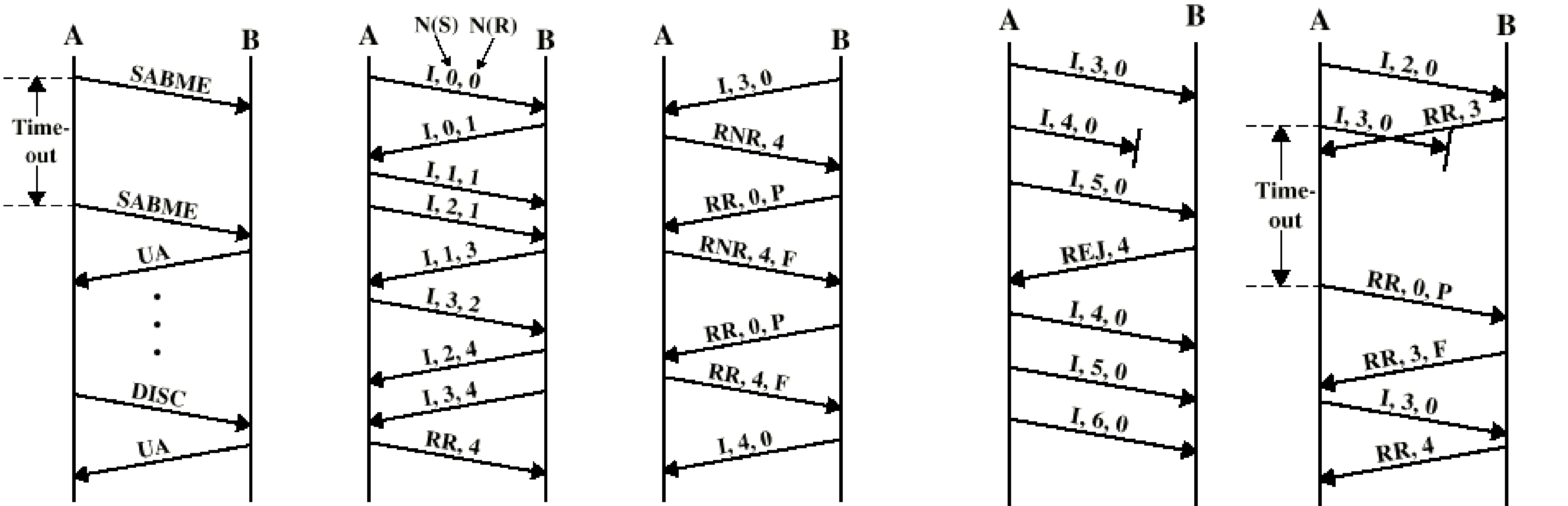
High-Level Data Link Control

- HDLC, Data Link Control, bit oriented

Bits	8	8	8	≥ 0	16	8
	0 1 1 1 1 1 1 0	Address	Control	Data	Checksum	0 1 1 1 1 1 1 0

- Framing – FLAGS
- Bit stuffing
- Error detection – ITU-16
- ARQ – Selective Repeat ARQ
- Used as basis for many telecom networks
  - » GSM/GPRS/UMTS, Frame Relay
  - » LAP-x protocols

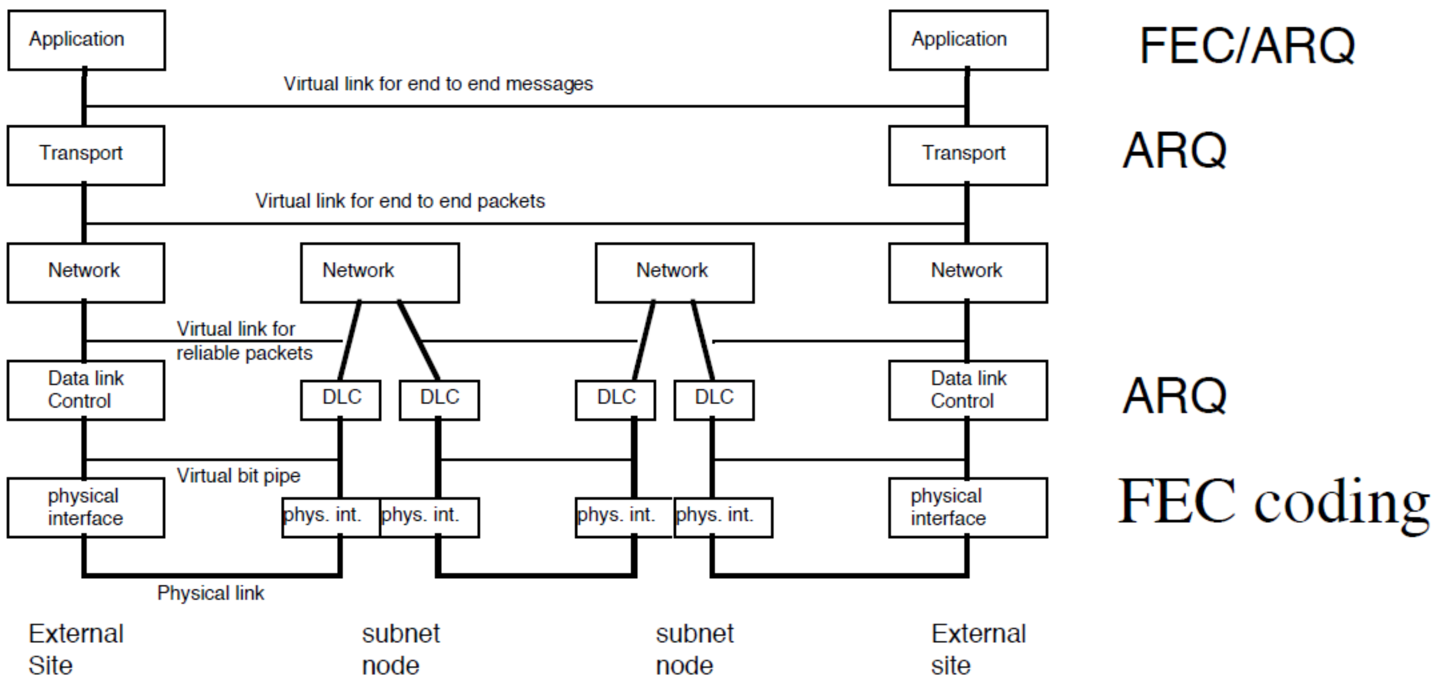
HDLC - Examples



(a) Link setup and disconnect (b) Two-way data exchange (c) Busy condition (d) Reject recovery (e) Timeout recovery

Reliability in the Protocol Stack

Reliability in the Protocol Stack



Reliability in the TCP/IP Reference Model

- The TCP/IP reference model assumes
  - » Layer 2 offers an error free service to the upper layer
  - » Service Data Units are
    - – delivered to upper layer without error,
    - – or discarded

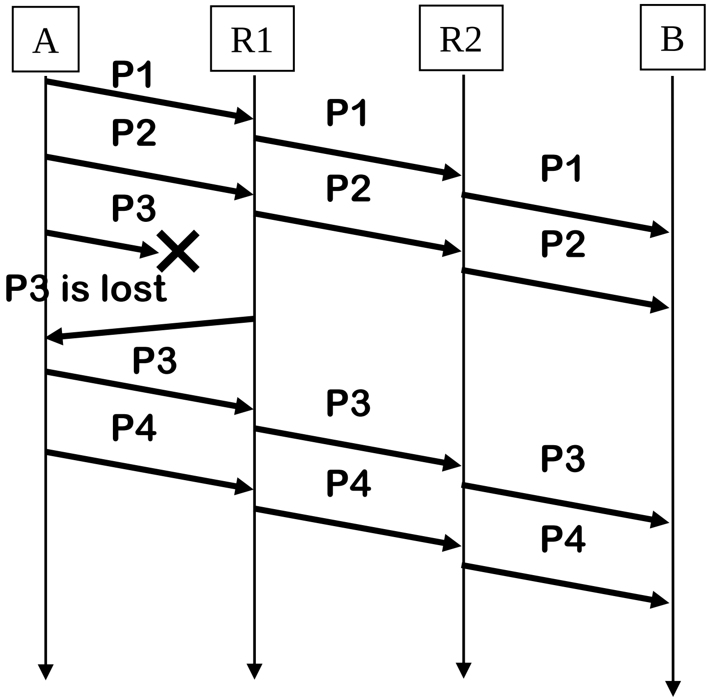
$$FER = 1 - (1 - BER)^n$$

- The layered model transforms bit error in packet losses

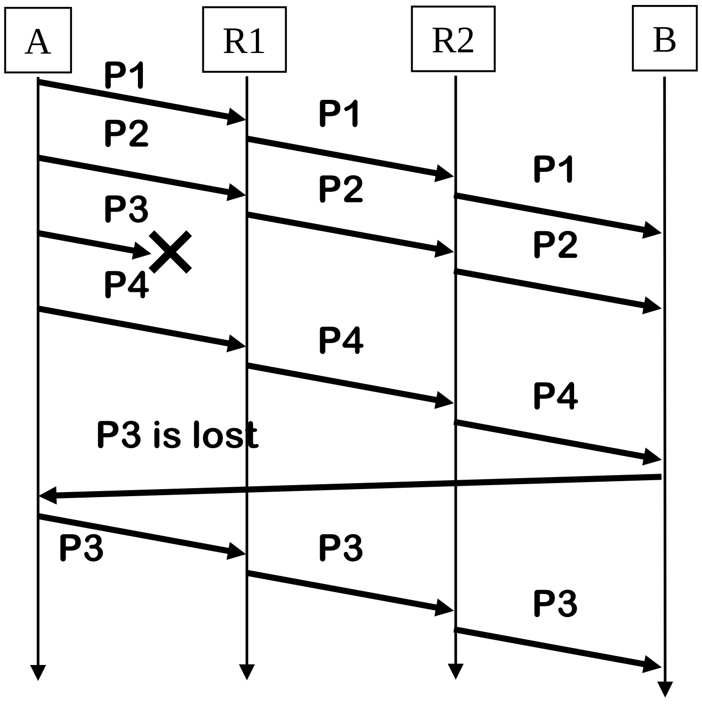
  Therefore, packet losses must be repaired ➔ ARQ solutions

- Two strategies can be used
  - » Link-by-Link ARQ
  - » End-to-end ARQ

Link-by-Link ARQ versus End-to-End ARQ



Link-by-Link ARQ
(data link layer)

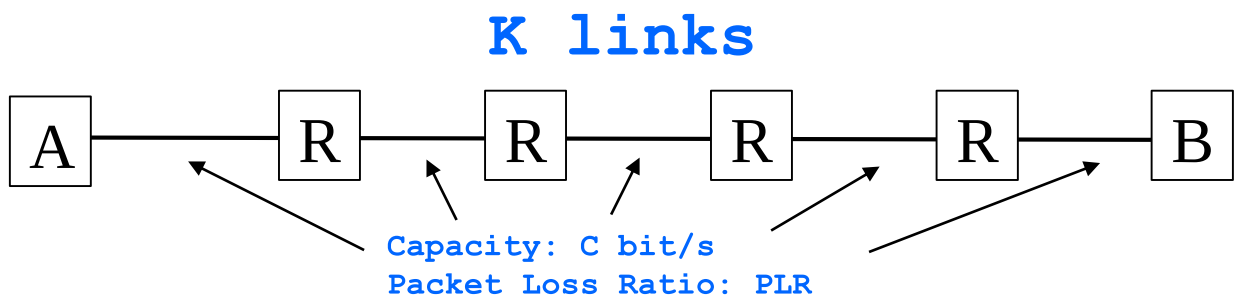


End-to-End ARQ
(transport or Application layers)

Link-by-Link ARQ versus End-to-End ARQ

- Link-by-Link ARQ
  - » Repairs losses link by link
  - » Requires network elements to
    - – remember information about packet flows ➔ high processing per frame
    - – store packets in case they have to be retransmitted ➔ memory required
- End-to-end ARQ
  - » Low complexity in intermediate network elements
    - – Switches/routers become simpler
  - » Packets may follow different end-to-end paths
  - » But, not acceptable when Packet Loss Ratio is high
  - » Let’s see why …

End to End Capacity



k	PLR	C_{EE}	C_{LL}
10	0.05	**0.6*C**	0.95 *C
10	0.0001	0.9990 *C	0.9999 *C

- Packet Loss Ratio (PLR)
- Capacity of one link $\mathbf{C_l=C*(1-PLR)}$
- End to End capacity
  - » using Link-by-Link ARQ: $\mathbf{C_{LL}=C_l=C*(1-PLR)}$
  - » Using End-to-End ARQ: $\mathbf{C_{EE}=C*(1-PLR)^K}$
- End-to-end ARQ ➔ **Inefficient when PLR is High**

ARQ in the TCP/IP Reference Model

- In the TCP/IP reference model, packet losses are repaired
  - At the Data Link layer on lossy channels (e.g. wireless data links)
  - At the end systems (transport layer or application layer)

Homework

1. Review slides

2. Read from Tanenbaum
   » Chapter 3 (5th edition)

3. Read from Bertsekas&Gallager
   » Sections 2.3, 2.4

4. Answer questions at moodle