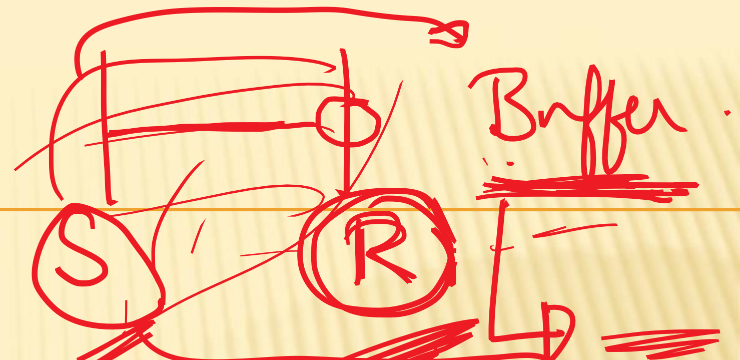
DATA LINK CONTROL PROTOCOLS
CHAPTER 7

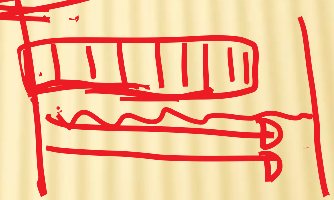
DATA LINK CONTROL PROTOCOLS

- need layer of logic above Physical
- to manage exchange of data over a link
  - frame synchronization
  - flow control
  - error control
  - addressing
  - control and data
  - link management

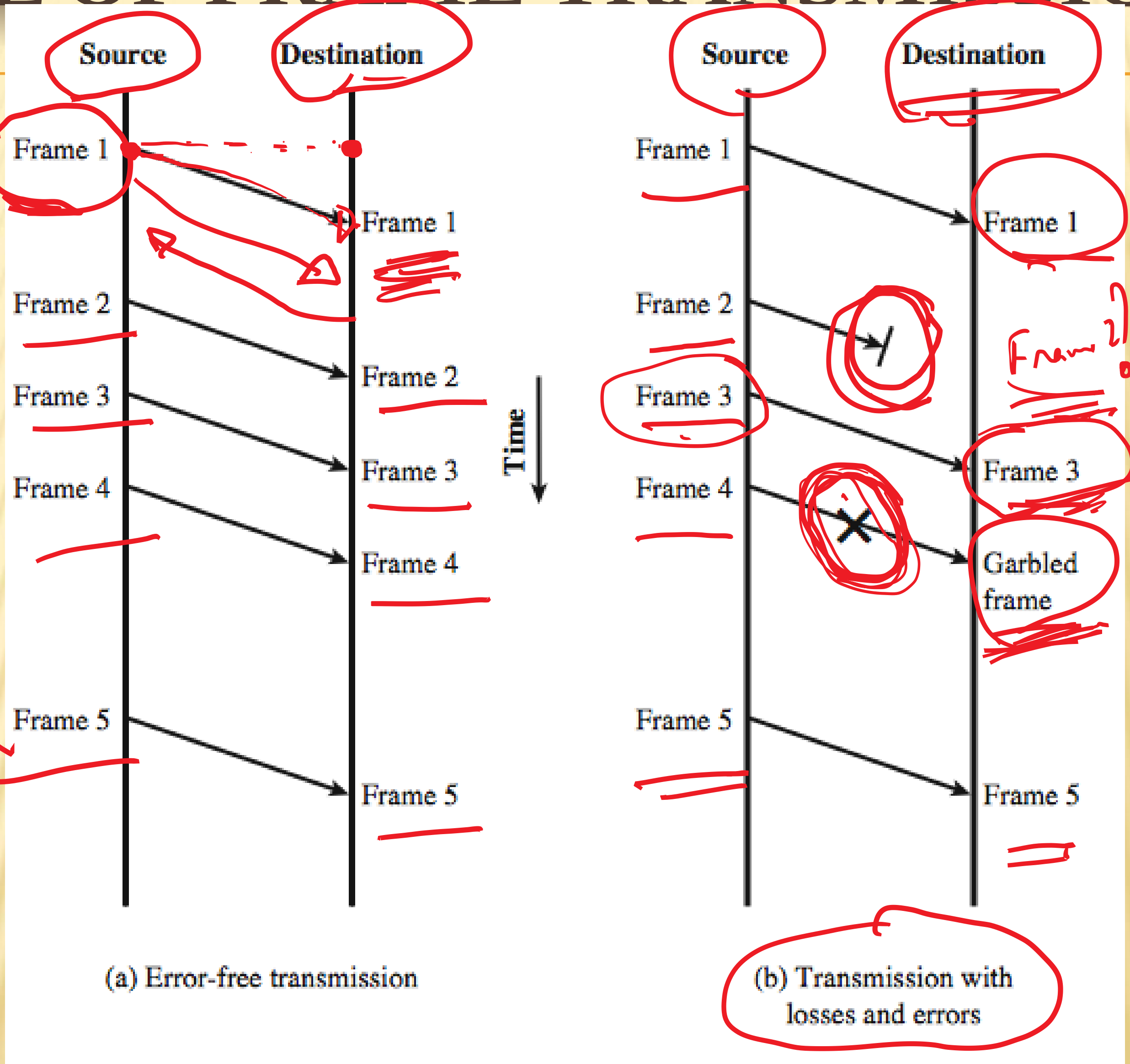
FLOW CONTROL



- ensure sending entity does not overwhelm receiving entity
  - by preventing buffer overflow
- influenced by:
  - transmission time
    - time taken to emit all bits into medium
  - propagation time
    - time for a bit to traverse the link
- assume here no errors but varying delays

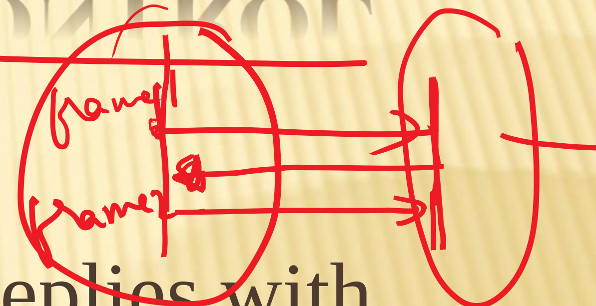


MODEL OF FRAME TRANSMISSION



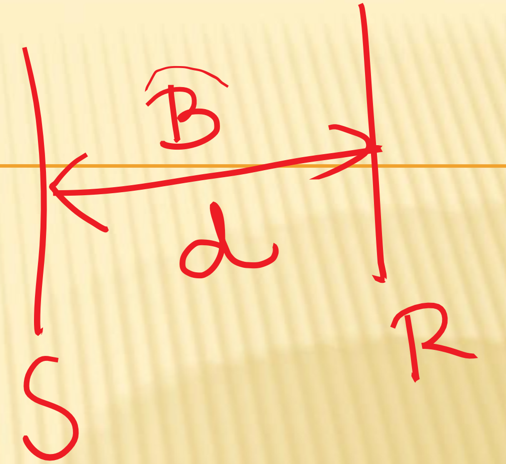
Vertical time sequence diagram

STOP AND WAIT FLOW CONTROL



- source transmits frame
- destination receives frame and replies with acknowledgement (ACK)
- source waits for ACK before sending next frame
- destination can stop flow by not sending ACK
- works well for a few large frames
- Stop and wait becomes inadequate if large block of data is split into small frames ?

CONTINUED…



- $B = R \,.\, (d/V)$ $B = R \times \frac{d}{V}$
  - B: length of the link in bits
  - R: data rate of the link, in bps
  - d: length or distance of the link in meters
  - V: velocity of propagation, in m/s

$a = \frac{\text{length of link in bits}}{\text{no. of bits in frame}}$

- $a = B/L$ $B = aL$
  - a: the propagation delay (with frame transmission time = 1)
  - L: the number of bits in the frame
- or $$a = (\frac{d}{V}) / (\frac{L}{R})$$

$aL = R \cdot \frac{d}{V}$

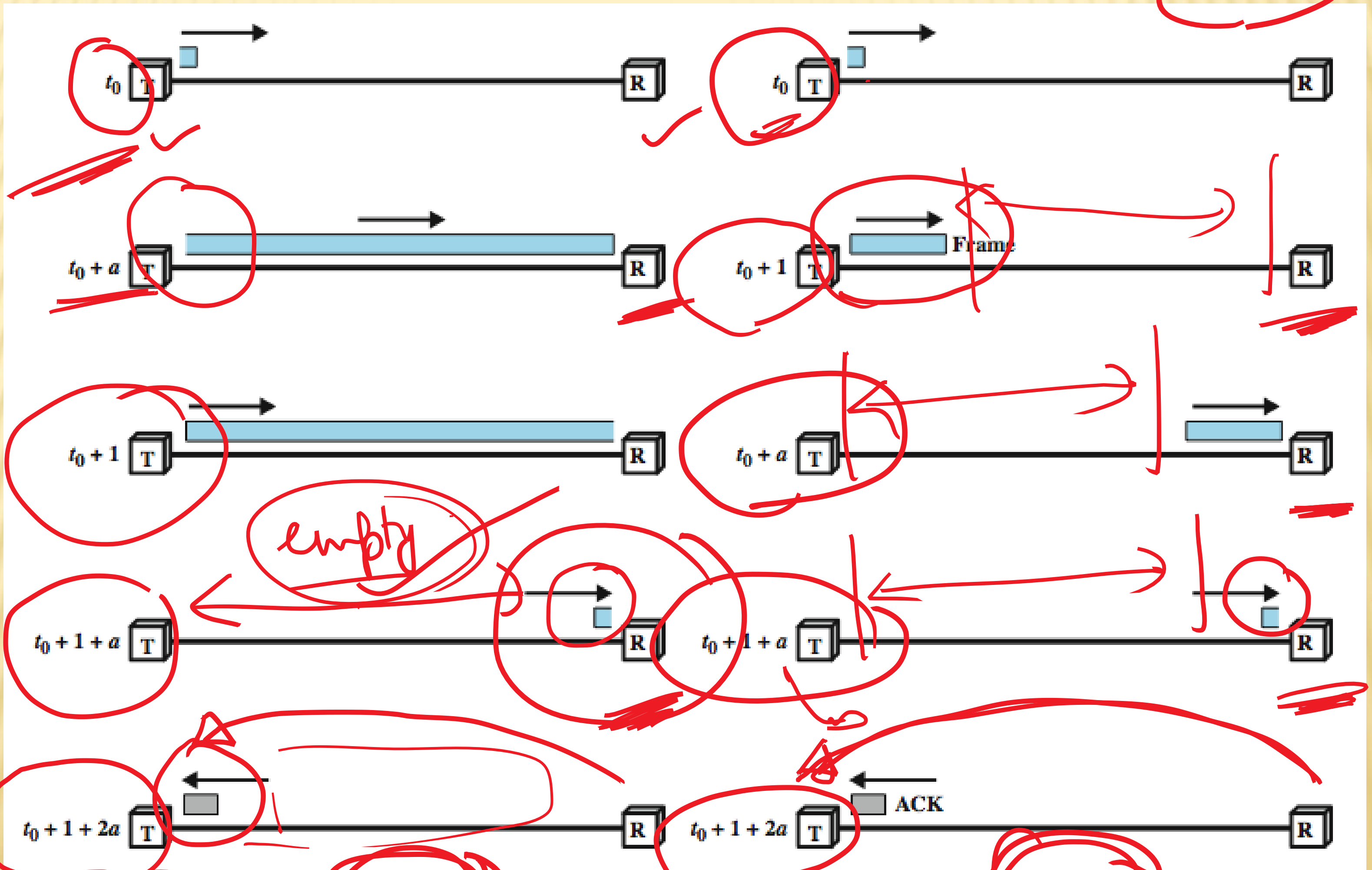
$a = \frac{R}{L} \times \frac{d}{V}$

$a = \frac{d/v}{L/R}$

Transmission time = 1

STOP AND WAIT LINK UTILIZATION

a



(a) $a < 1$ (b) $a > 1$

SLIDING WINDOW FLOW CONTROL

- allows multiple numbered frames to be in transit
- receiver has buffer space of W frames long
- transmitter sends up to W frames without ACK
- ACK includes number of next frame expected
- sequence number is bounded by size of field (k)
  - frames are numbered modulo 2^k
  - giving max window size of up to $2^k – 1$

3

3

$2^3 \Rightarrow 8$

- receiver can acknowledge frames without permitting further transmission (Receive Not Ready)
- must send a normal acknowledge to resume
- if we have full-duplex link, can piggyback ACKs

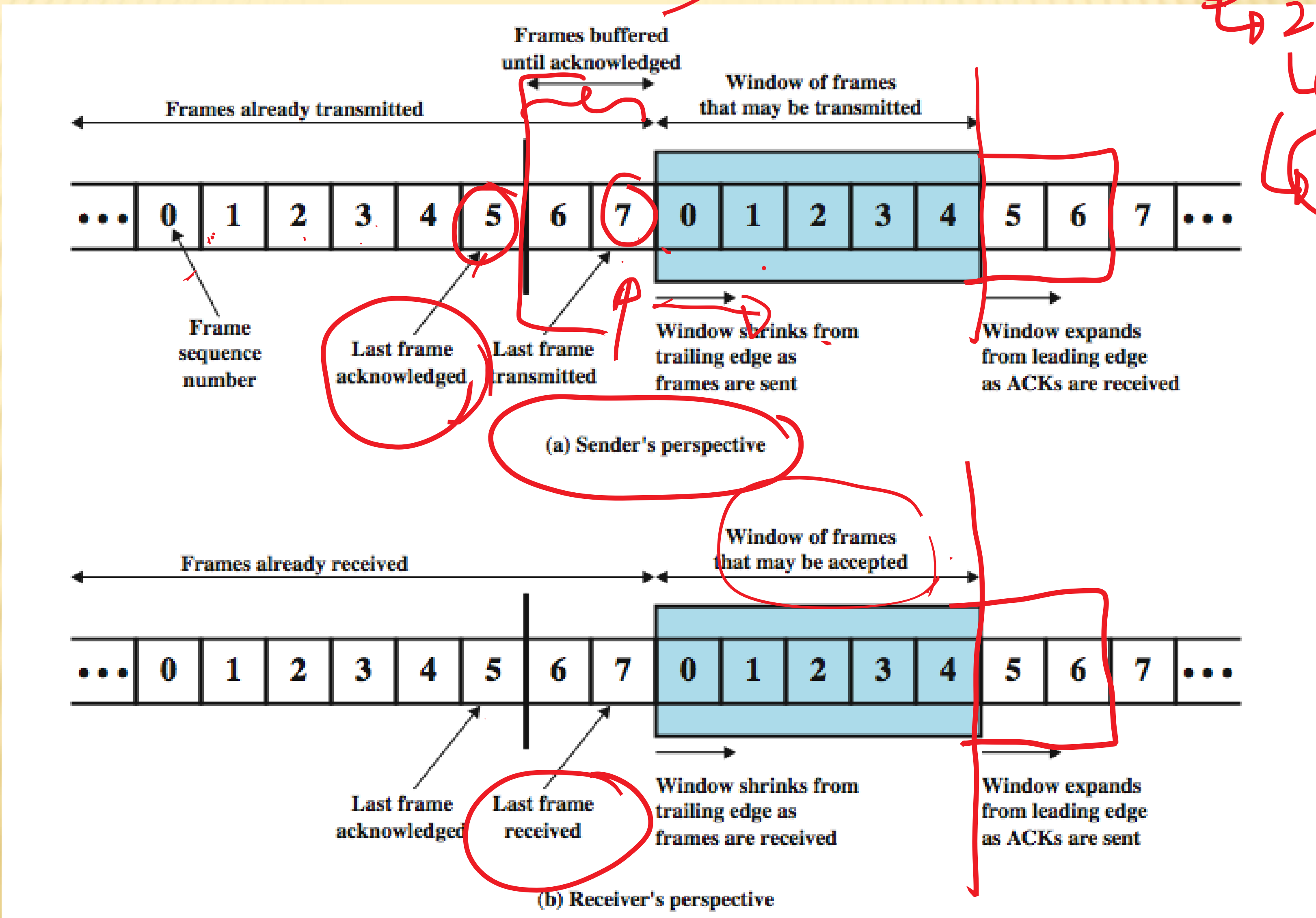
0 to 7

0, 1, 2, 3, 4, 5, 6, 7

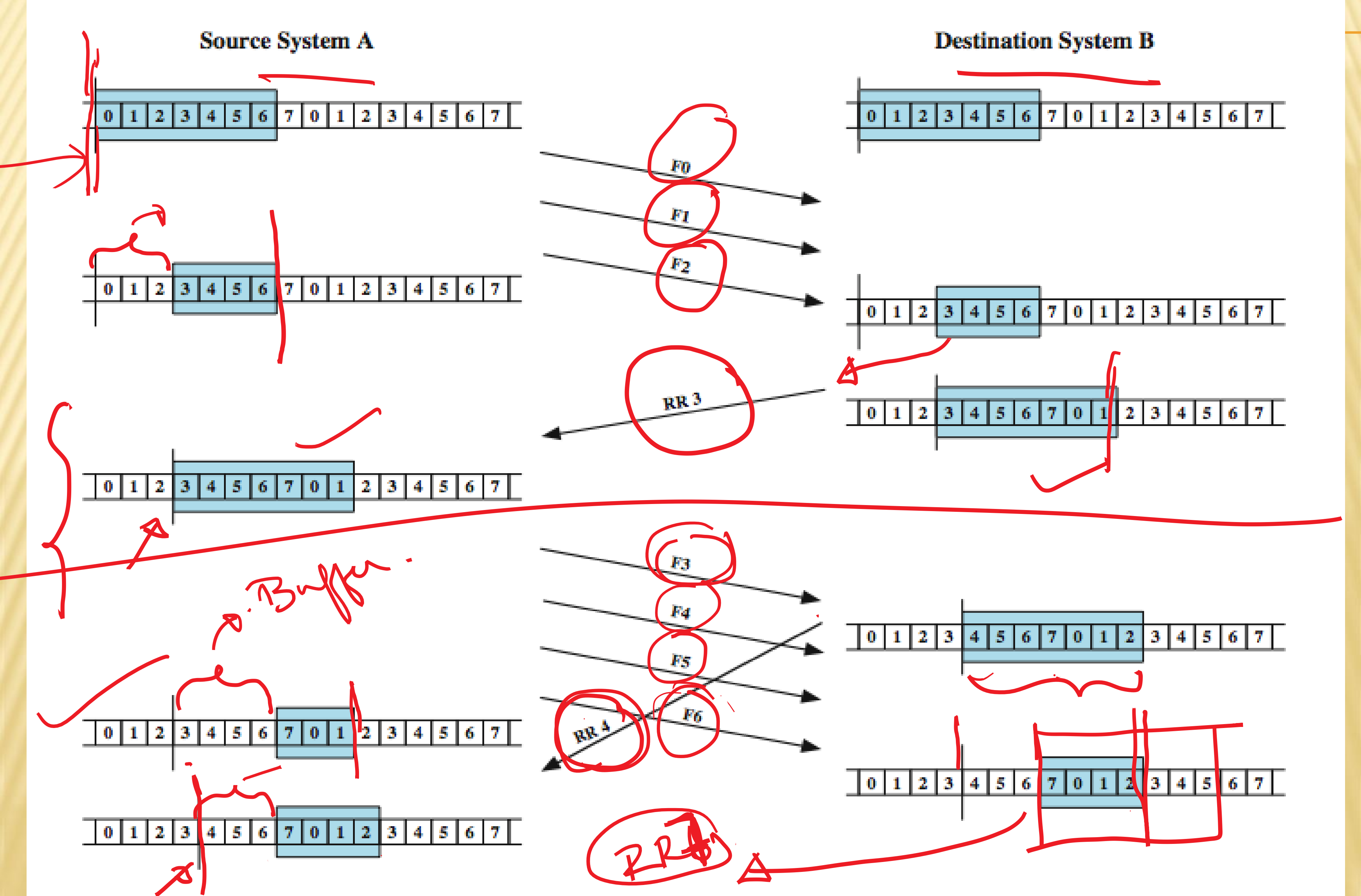
window 7

SLIDING WINDOW DIAGRAM

3-bit → 8 → 0 to 7
→ $2^k - 1$ → 7 → 0 to 6



SLIDING WINDOW EXAMPLE



EXAMPLE 7.1 Consider a 200-m optical fiber link operating at 1 Gbps. The velocity of propagation of optical fiber is typically about 2×10^8 m/s. Using Equation (7.1), $B = (10^9 \times 200)/(2 \times 10^8) = 1000$ bits. Assume a frame of 1000 octets, or 8000 bits, is transmitted. Using Equation (7.2), $a = (1000/8000) = 0.125$. Using Figure 7.2a as a guide, assume transmission starts at time $t = 0$. After 1 μs (a normalized time of 0.125 frame times), the leading edge (first bit) of the frame has reached R, and the first 1000 bits of the frame are spread out across the link. At time $t = 8\ \mu$s, the trailing edge (final bit) of the frame has just been emitted by T, and the final 1000 bits of the frame are spread out across the link. At $t = 9\ \mu$s, the final bit of the frame arrives at R. R now sends back an ACK frame. If we assume the frame transmission time is negligible (very small ACK frame) and that the ACK is sent immediately, the ACK arrives at T at $t = 10\ \mu$s. At this point, T can begin transmitting a new frame. The actual transmission time for the frame was 8 μs, but the total time to transmit the first frame and receive and ACK is 10 μs. → 10 μs.

$$B = R \times \frac{d}{V} = \frac{1 \times 10^9 \times 200}{2 \times 10^8}$$

Frame size: 8000 bits.

$$a = \frac{1000}{8000}$$

$a > 1$

$a < 1$

EXAMPLE 7.3 Let us consider the use of sliding-window flow control for the two configurations of Example 7.1. As was calculated in Example 7.1, it takes 10 μs for an ACK to the first frame to be received. It takes 8 μs to transmit one frame, so the sender can transmit one frame and part of a second frame by the time the ACK to the first frame is received. Thus, a window size of 2 is adequate to sender to transmit frames continuously, or a rate of one frame every 8 μs. With stop-and-wait, a rate of only one frame per 10 μs is possible.

10 μs

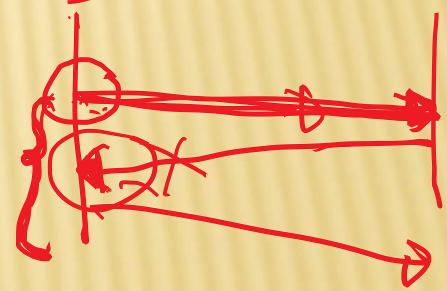
8 μs.

2 μs.

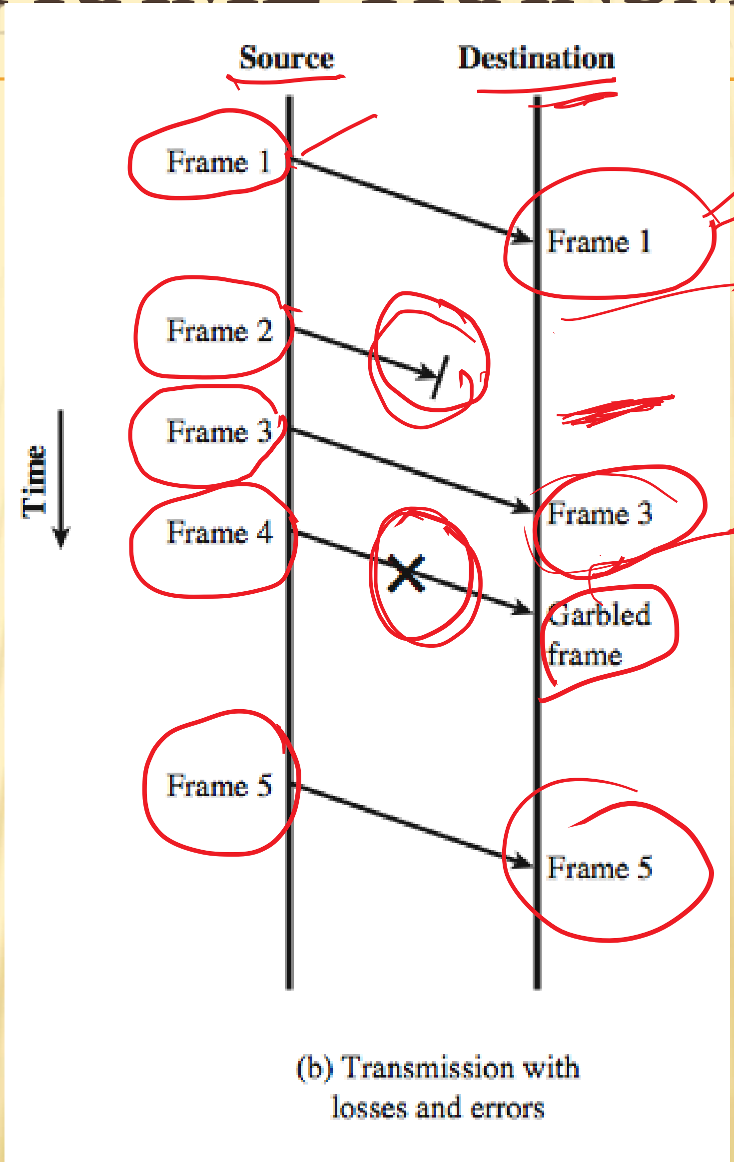
10 μs.

ERROR CONTROL

- detection and correction of errors such as:
  - lost frames
  - damaged frames
- common techniques for error control: Send Receiver
  - error detection
  - positive acknowledgment
  - retransmission after timeout
  - negative acknowledgement & retransmission



MODEL OF FRAME TRANSMISSION



Vertical time sequence diagram

AUTOMATIC REPEAT REQUEST (ARQ)

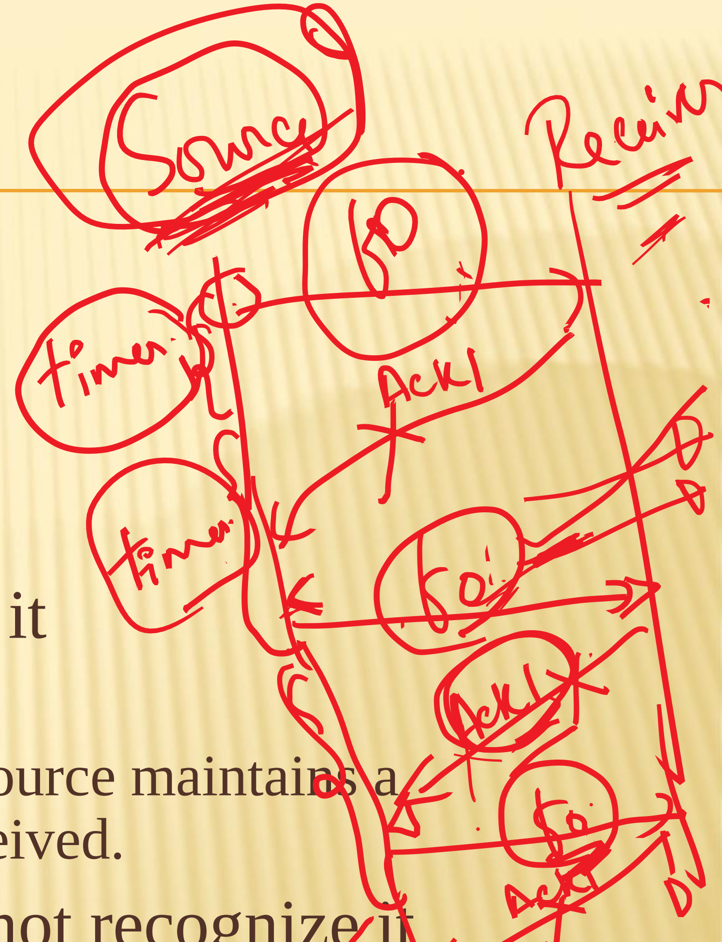
The effect of ARQ is to turn an unreliable data link into a reliable one. Three versions of ARQ are:

- stop and wait ARQ ✓ → Stop & wait flow control.
- Go-back-N ARQ ✓
- Selective-reject ARQ (selective retransmission) ✓

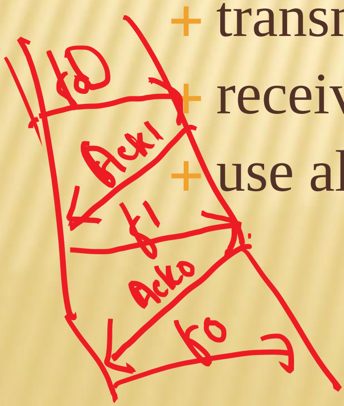
Sliding window flow control.

STOP AND WAIT ARQ

- source transmits single frame
- wait for ACK
- 2 types of error occurs:
  - if received frame damaged, discard it
    - +transmitter has timeout
    - +if no ACK within timeout, retransmit. Source maintains a transmitted frame copy until ACK is received.
  - if ACK damaged, Transmitter will not recognize it
    - + transmitter will retransmit
    - + receive gets two copies of frame
    - + use alternate numbering and ACK0 / ACK1

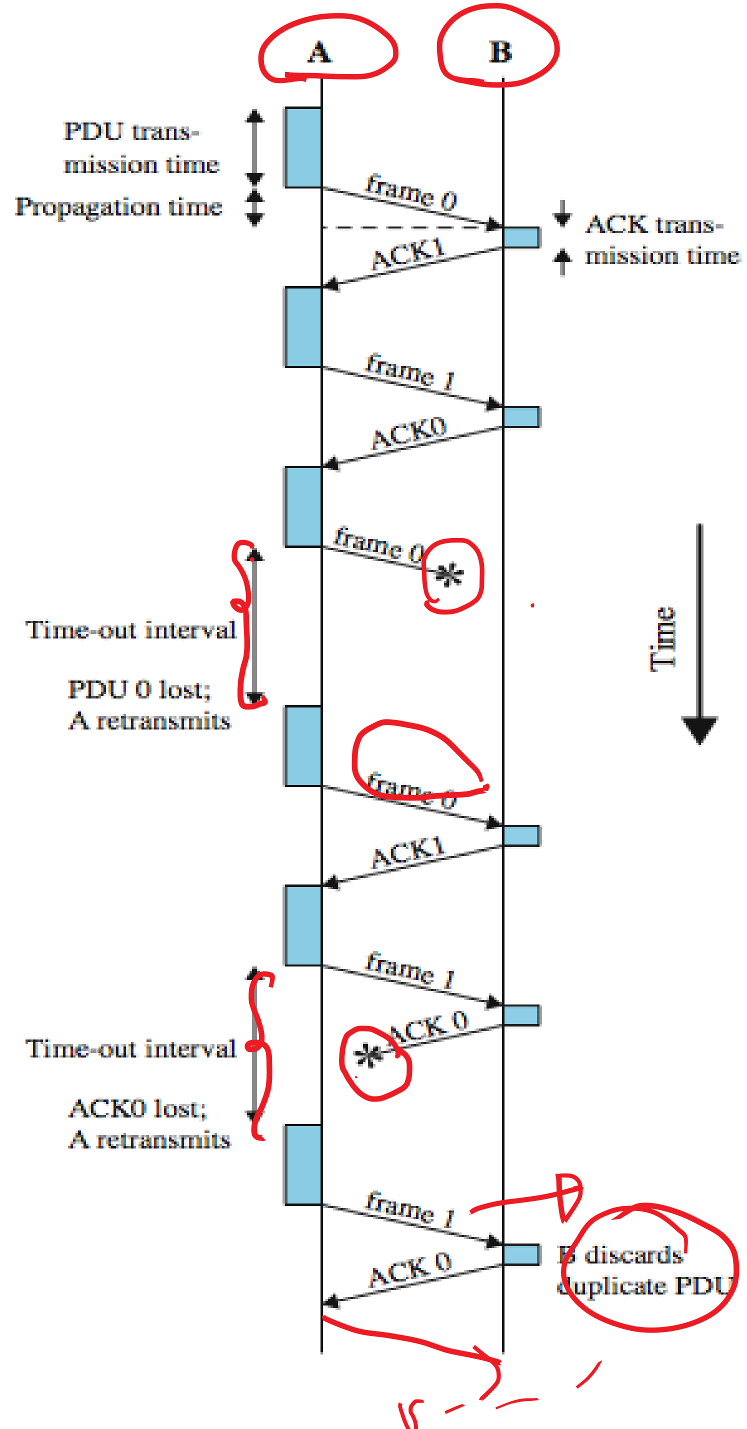


frame0, frame1, frame0, frame1



STOP AND WAIT ARQ

- Advantage:
  - Simple

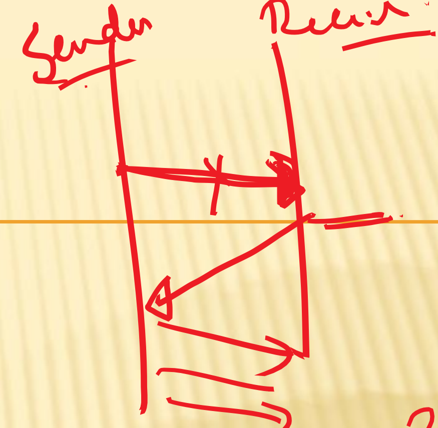


GO-BACK-N ARQ

- based on sliding window
- if no error, ACK as usual
- if error, reply with rejection(REJ)
  - discard that frame and all future frames until error frame received correctly.
  - transmitter must go back and retransmit that frame and all subsequent frames

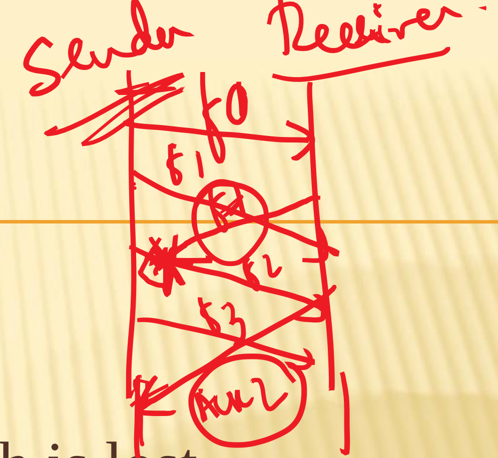
GO-BACK-N - HANDLING

ARQ

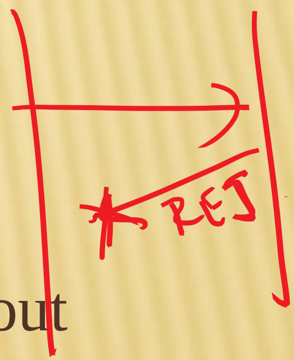


- Damaged Frame
  - error in frame *i* so receiver rejects frame *i* .
  - transmitter retransmits frames from *i*
- Lost Frame
  - frame *i* lost
    - transmitter sends *i+1* and receiver gets frame *i+1* out of seq and rejects frame *i* (REJ i)
    - or transmitter times out and send ACK with P bit set which receiver responds to with ACK *i*
  - transmitter then retransmits frames from *i*

GO BACK N - HANDLING

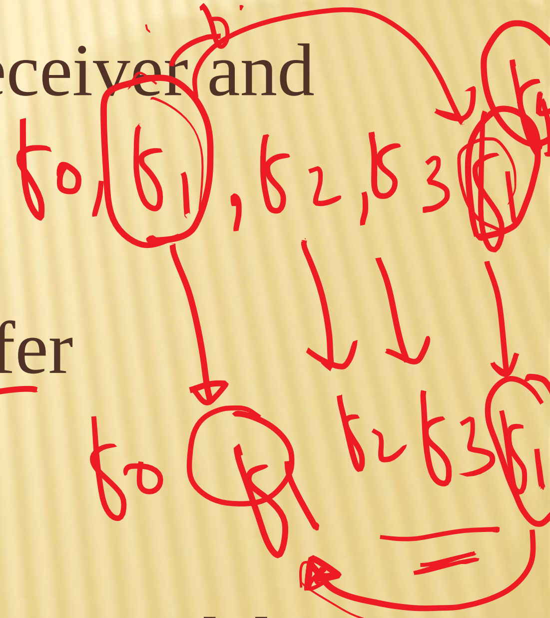


- Damaged Acknowledgement
  - receiver gets frame *i*, sends ack (*i+1*) which is lost
  - Ack's are cumulative, so next ACK (*i+n*) may arrive before transmitter times out on frame *i*
  - if transmitter times out, it sends ack with P bit set
  - can be repeated a number of times before a reset procedure is initiated
- Damaged Rejection
  - reject for damaged frame is lost
  - handled as for lost frame when transmitter times out



SELECTIVE-REJECT(ARQ)

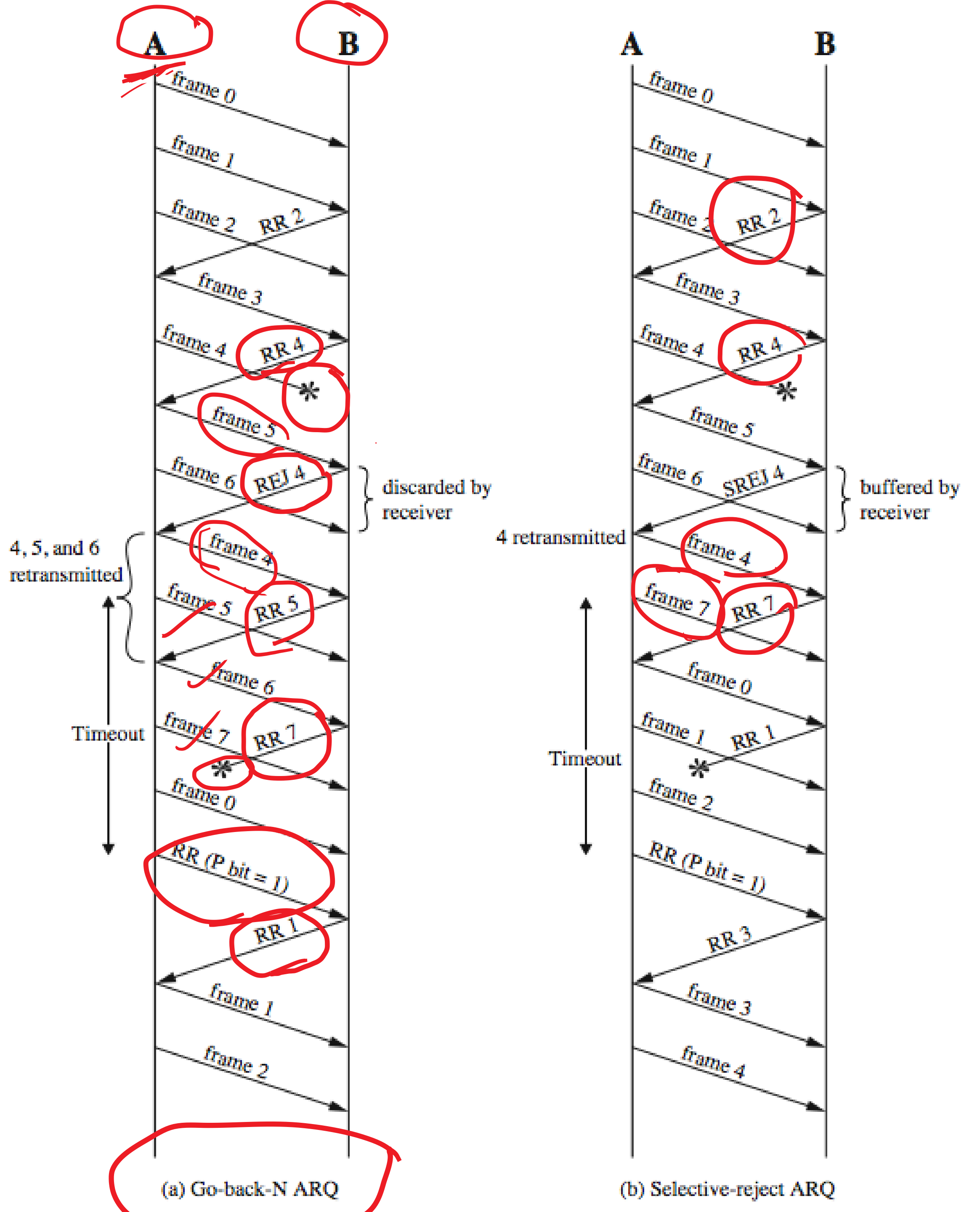
- only rejected frames are retransmitted
- subsequent frames are accepted by the receiver and buffered
- minimizes retransmission
- receiver must maintain large enough buffer
- more complex logic in transmitter
- hence less widely used
- useful for satellite links with long propagation delays



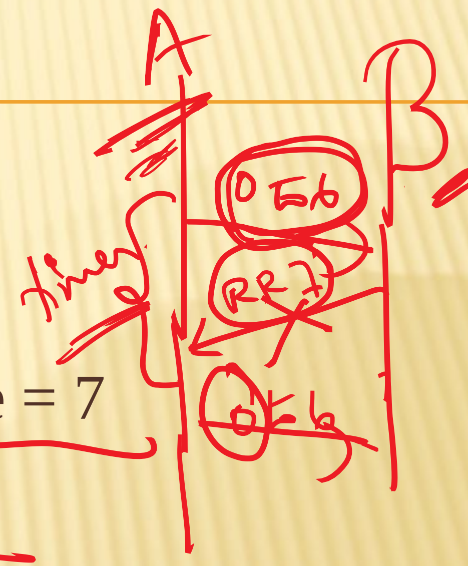
Receive Ready (RR)

GO-BACK-N VS SELECTIVE-REJECT

Selective Reject → SREJ



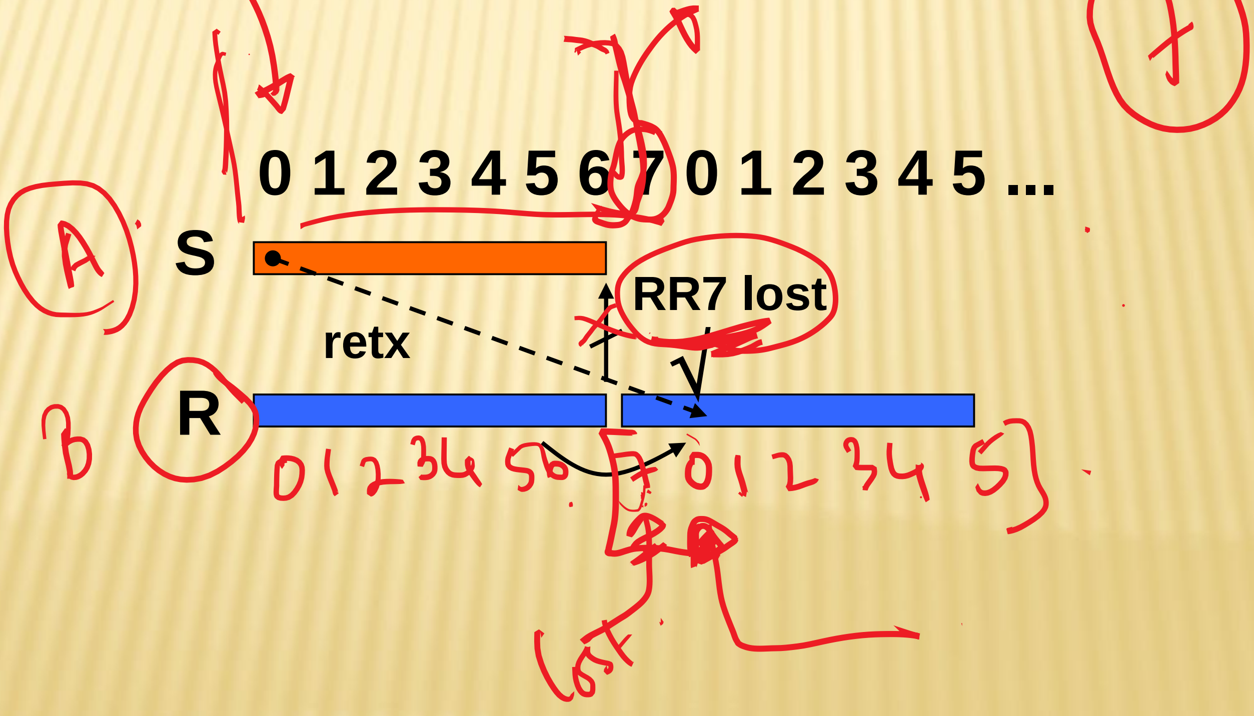
SELECTIVE-REJECT ARQ



- Window-size limitation
  - E.g. 3 bit sequence number, window size = 7
  - Station A sends frames 0 ~ 6 to station B
  - Station B receives all seven frames and cumulatively acknowledges with RR7
  - If RR 7 is lost
  - A times out and retransmit frame 0

SELECTIVE-REJECT ARQ (CONT)

- B has already advanced its receive window to accept frames 7, 0, 1, 2, 3, 4, and 5. Thus, it assumes that frame 7 has been lost and that this is a new frame 0 which it accepts.

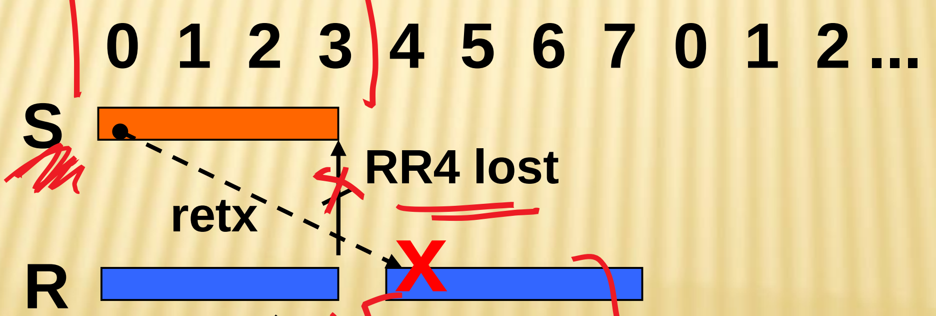


SELECTIVE-REJECT ARQ

- Problem with the foregoing scenario
  - overlay between the sending and receiving windows
- Solution
  - for a k-bit sequence number, the maximum window size is limited to 2^{k-1}.

$2^3 - 1 = 7$

$2^{(k-1)} = 2^{(3-1)} = 2^2 = 4$



0 1 2 3 4 5 6 7 0 1 2

STOP AND WAIT FLOW CONTROL PERFORMANCE ISSUES

$$T_F = t_{prop} + t_{frame} + t_{proc} + t_{prop} + t_{ack} + t_{proc}$$

$T_F = 2t_{prop} + t_{frame}.$

total time :

$$T = n(2t_{prop} + t_{frame})$$

utilization or efficiency of the line :

$$u = \frac{n \times t_{frame}}{n(2t_{prop} + t_{frame})} = \frac{t_{frame}}{2t_{prop} + t_{frame}} = \frac{1}{2\frac{t_{prop}}{t_{frame}} + 1}$$

?

$$a = \frac{t_{prop}}{t_{frame}}$$

$$u = \frac{1}{1 + 2a}$$

$$a = \frac{\text{Propagation Time}}{\text{Transmission Time}}$$

$$a = \frac{d/V}{L/R} = \frac{Rd}{VL}$$

d → distance of link.

V → Velocity of propagation

L → length of frame

R → data rate.

$d = 10^6$ m

EXAMPLE 7.6 First, consider a wide area network (WAN) using ATM (asynchronous transfer mode, described in Part Three), with the two stations a thousand kilometers apart. The standard ATM frame size (called a cell) is 424 bits and one of the standardized data rates is 155.52 Mbps. Thus, transmission time equals $424/(155.52 \times 10^6) = 2.7 \times 10^{-6}$ seconds. If we assume an optical fiber

T/R d/V

link, then the propagation time is $(10^6 \text{ meters})/(2 \times 10^8 \text{ m/s}) = 0.5 \times 10^{-2}$ seconds. Thus, $a = (0.5 \times 10^{-2})/(2.7 \times 10^{-6}) \approx 1850$, and efficiency is only $1/3701 = 0.00027$.

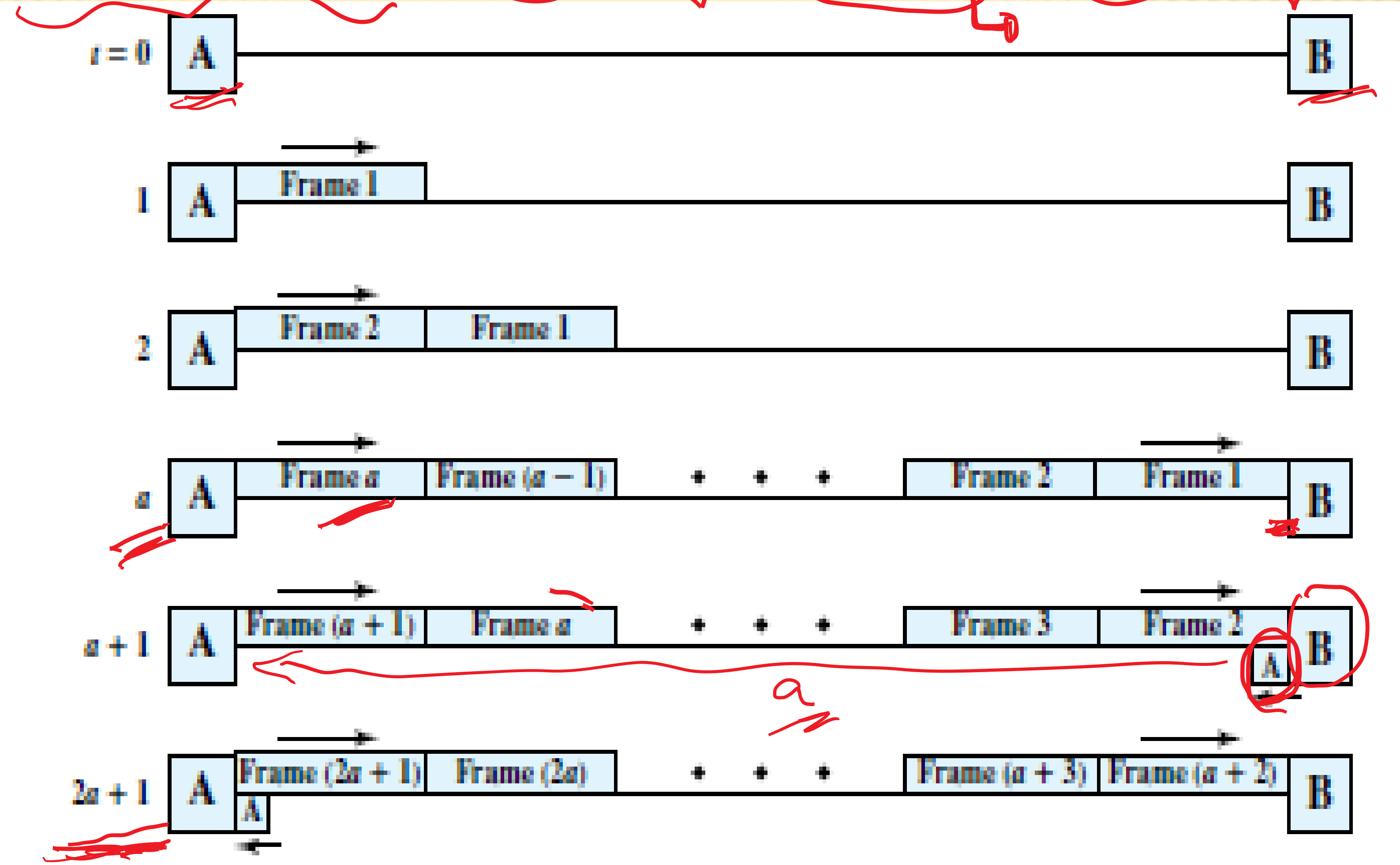
$T + 2a$

At the other extreme, in terms of distance, is the local area network (LAN). Distances range from 0.1 to 10 km, with data rates of 10 Mbps to 1 Gbps; higher data rates tend to be associated with shorter distances. Using a value of $V = 2 \times 10^8$ m/s, a frame size of 1000 bits, and a data rate of 10 Mbps, the value of a is in the range of 0.005 to 0.5. This yields a utilization in the range of 0.5 to 0.99. For a 100-Mbps LAN, given the shorter distances, comparable utilizations are possible.

We can see that LANs are typically quite efficient, whereas high-speed WANs are not. As a final example, let us consider digital data transmission via modem over a voice-grade line. A typical data rate is 56 kbps. Again, let us consider a 1000-bit frame. The link distance can be anywhere from a few tens of meters to thousands of kilometers. If we pick, say, as a short distance $d = 1000$ m, then $a = (56{,}000 \text{ bps} \times 1000 \text{ m})/(2 \times 10^8 \text{ m/s} \times 1000 \text{ bits}) = 2.8 \times 10^{-4}$, and utilization is effectively 1.0. Even in a long-distance case, such as $d = 5000$ km, we have $a = (56{,}000 \times 5 \times 10^6)/(2 \times 10^8 \times 1000 \text{ bits}) = 1.4$ and efficiency equals 0.26.

ERROR FREE SLIDING WINDOW FLOW CONTROL

- Window size W, transmission time = 1, propagation time = a

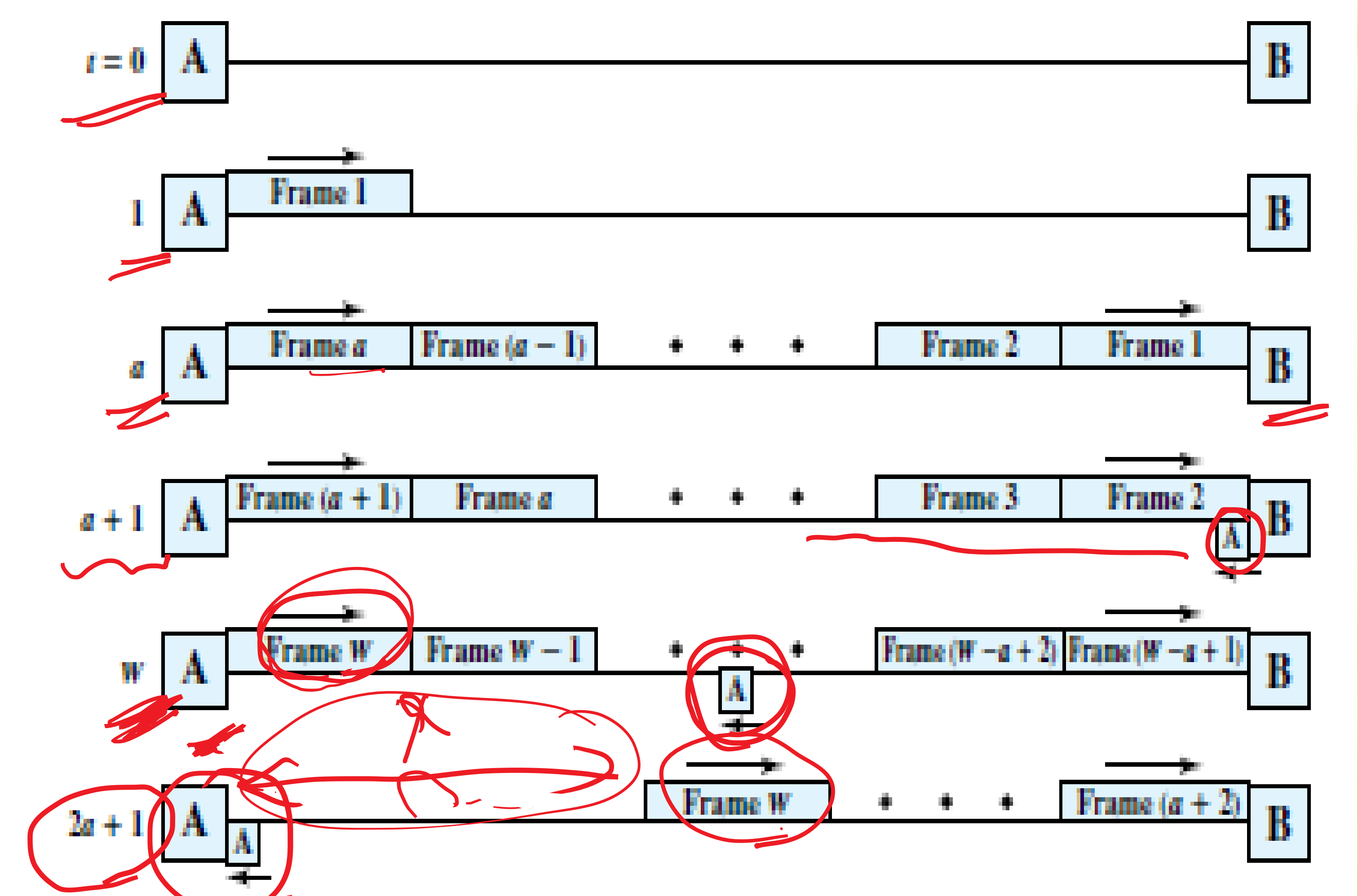


(a) $W \geq 2a + 1$

ERROR FREE SLIDING WINDOW FLOW CONTROL

- Window size W, transmission time = 1, propagation time = a
- Case 1: W >= 2a + 1
  - Sender A can transmit continuously with no pause and normalized throughput is 1.0
- Case 2: W < 2a + 1
  - Sender A exhausts its window at t = W and cannot send additional frames until t = 2a + 1.
  - Normalized throughput is W / (2a+1)

$$U = \begin{cases} 1 & W \geq 2a + 1 \\ \dfrac{W}{2a + 1} & W < 2a + 1 \end{cases}$$



t = 0
A
B
1
Frame 1
a
Frame a
Frame (a − 1)
Frame 2
Frame 1
a + 1
Frame (a + 1)
Frame a
Frame 3
Frame 2
W
Frame W
Frame W − 1
Frame (W − a + 2)
Frame (W − a + 1)
2a + 1
Frame W
Frame (a + 2)

(b) $W < 2a + 1$

ARQ

$$U = \frac{T_f}{T_t} \tag{7.7}$$

where

T_f = time for transmitter to emit a single frame

T_t = total time that line is engaged in the transmission of a single frame

For error-free operation using stop-and-wait ARQ,

$$U = \frac{T_f}{T_f + 2T_p}$$

where T_p is the propagation time. Dividing by T_f and remembering that $a = T_p/T_f$, we again have Equation (7.4). If errors occur, we must modify Equation (7.7) to

$$U = \frac{T_f}{N_r T_t}$$

Expected no. of transmissions of a frame.

$P \to$ Probability of error.

$$U = \frac{1}{N_r(1+2a)}$$

$i \{ (1-P) \to$ without error; $(i-1) \to$ with error $\to P$

$$U = \frac{1}{N_r(1 + 2a)} = \frac{1}{\left[\frac{1}{(1-P)}\right]\{1+2a\}}$$

$$N_r = \mathrm{E}[\text{transmissions}] = \sum_{i=1}^{\infty}(i \times \Pr[i \text{ transmissions}]) = \sum_{i=1}^{\infty}(iP^{i-1}(1 - P)) = \frac{1}{1 - P}$$

$$= (1-P)\sum_{i=1}^{\infty} i P^{i-1} = (1-P) \times \frac{1}{(1-P)^2} = \frac{1}{1-P}$$

So we have

$$\textbf{Stop-and Wait:} \quad U = \frac{1 - P}{1 + 2a}$$

$$\sum_{i=1}^{\infty} i P^{(i-1)} = \frac{1}{(1-P)^2}$$

$U = \frac{1}{N_r}$, $\frac{W}{N_r(2a+1)}$; $U = \begin{cases} \frac{1}{N_r} ; & W \geq 2a+1 \\ \frac{W}{N_r(2a+1)} ; & W < 2a+1 \end{cases}$

$N_r = \frac{1}{1-P}$

Selective Reject:

$$U = \begin{cases} 1 - P & W \geq 2a + 1 \\ \frac{W(1 - P)}{2a + 1} & W < 2a + 1 \end{cases}$$

N_r = E[number of transmitted frames to successfully transmit one frame]

$$= \sum_{i=1}^{\infty} f(i) P^{i-1}(1 - P)$$

Go Back n

where $f(i)$ is the total number of frames transmitted if the original frame must be transmitted i times. This can be expressed as

$$f(i) = 1 + (i - 1)K$$
$$= (1 - K) + Ki$$

Substituting yields[5]

$$N_r = (1 - K)\sum_{i=1}^{\infty} P^{i-1}(1 - P) + K\sum_{i=1}^{\infty} iP^{i-1}(1 - P)$$

$$= 1 - K + \frac{K}{1 - P}$$

$$= \frac{1 - P + KP}{1 - P}$$

$\frac{1}{(1-P)}$ $\sum_{i=1}^{\infty} P^{i-1} = \frac{1}{1-P}$

$$\frac{W}{(2a+1)N_r}$$

Go-back-N: $$U = \begin{cases} \dfrac{1-P}{1+2aP} & W \geq 2a+1 \\ \dfrac{W(1-P)}{(2a+1)(1-P+WP)} & W < 2a+1 \end{cases}$$

$$U = \frac{1}{N_r} = \frac{1}{\frac{1-P+KP}{1-P}} = \frac{1-P}{1-P+(2a+1)P} = \frac{1-P}{1+2aP}$$

$K = 2a+1$; $W \geq 2a+1$

$K = W$; $W < 2a+1$

HIGH LEVEL DATA LINK CONTROL (HDLC)

- an important data link control protocol

Defines

- 3 station types:
  - Primary - controls operation of link
  - Secondary - under control of primary station
  - Combined - issues commands and responses

command-
response

- 2 link configurations
  - Unbalanced - 1 primary, multiple secondary. Supports full duplex and half duplex transmission.
  - Balanced - 2 combined stations and supports full duplex and half duplex.

CONT…

- **3 data Transfer Modes**
- Normal Response Mode (NRM)
  - unbalanced configuration, primary initiates transfer
  - used on multi-drop lines, many terminals are connected to host computer.
- Asynchronous Balanced Mode (ABM)
  - balanced configuration, either station initiates transmission without receiving permission from other combined station, has no polling overhead, widely used
- Asynchronous Response Mode (ARM)
  - unbalanced configuration, secondary may initiate transmit without permission from primary, primary holds responsibility for the line, rarely used

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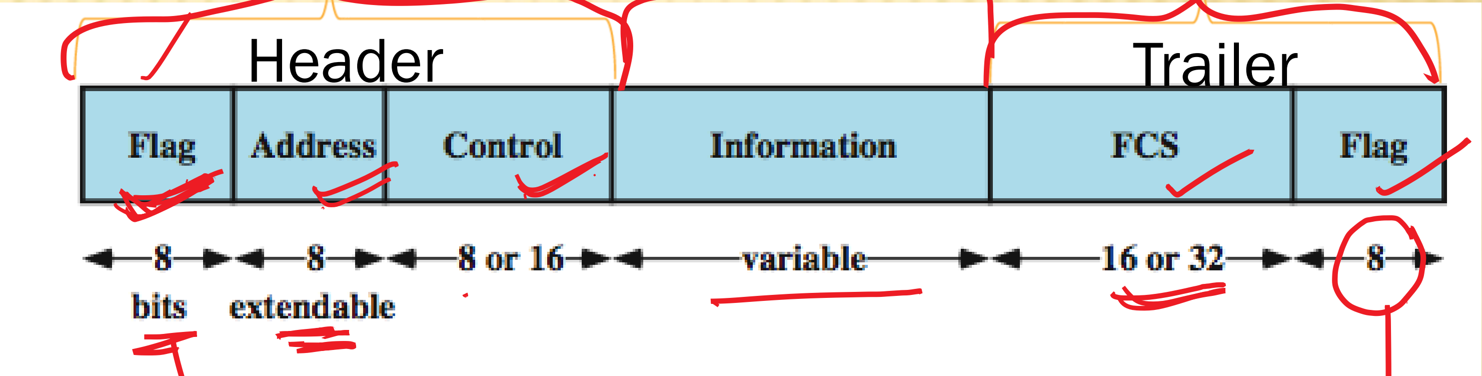
HDLC FRAME STRUCTURE

- synchronous transmission of frames
- single frame format used



(a) Frame format

FLAG FIELDS AND BIT STUFFING

- delimit frame at both ends with 01111110 seq
- receiver hunts for flag sequence to synchronize
- bit stuffing used to avoid confusion with data containing flag sequence 01111110
  - 0 inserted after every sequence of five 1s
  - if receiver detects five 1s it checks next bit
  - if next bit is 0, it is deleted (was stuffed bit)
  - if next bit is 1 and seventh bit is 0, accept as flag
  - if sixth and seventh bits 1, sender is indicating abort

01111110

Receiving end

01111110 flag

Original Pattern:

111111111111011111101111110

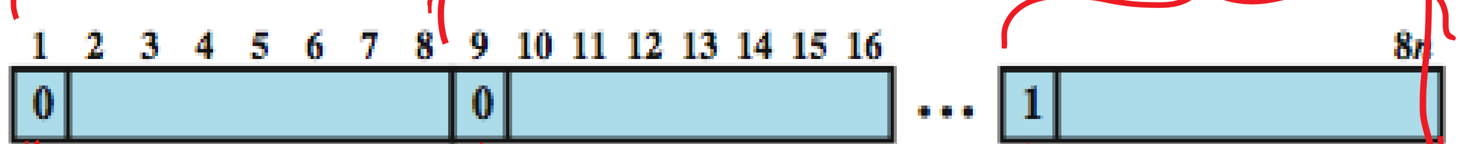
After bit-stuffing

Received

1111101111101101111101011111010

ADDRESS FIELD

- identifies secondary station that sent or will receive frame
- usually 8 bits long
- may be extended to multiples of 7 bits
  - Left most bit of each octet indicates if it is the last octet (1) or not (0)
- all ones address 11111111 is broadcast

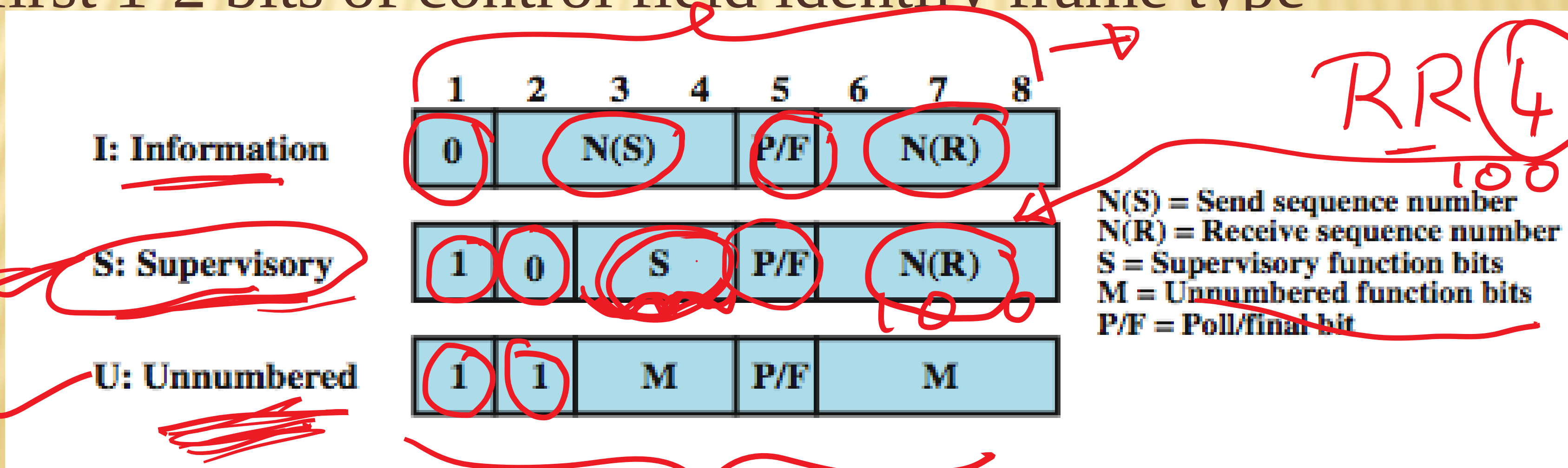


(b) Extended Address Field

16 - bits

CONTROL FIELD

- different for different frame type
  - Information - data transmitted to user
    - Flow and error control piggybacked on information frames
  - Supervisory - ARQ when piggyback not used
  - Unnumbered - supplementary link control
- first 1-2 bits of control field identify frame type



(c) 8-bit control field format

CONTROL FIELD

- use of Poll/Final bit depends on context
- in command frame is P bit set to1 to solicit (poll) response from transmitter
- in response frame is F bit set to 1 to indicate response to soliciting command
- seq number usually 3 bits
  - can extend to 8 bits as shown below

Flag | CFI | Flag Flag

3-bit

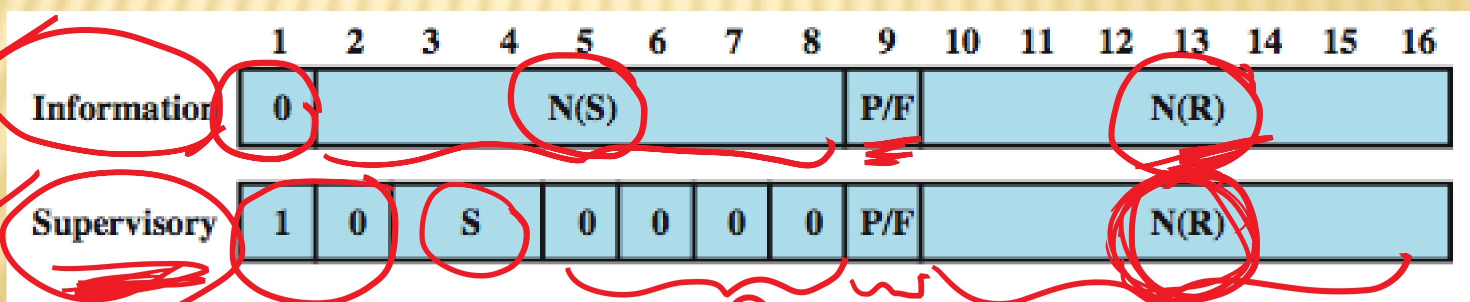
0, 1, 2, 3, 4, 5, 6, 7

8-bit

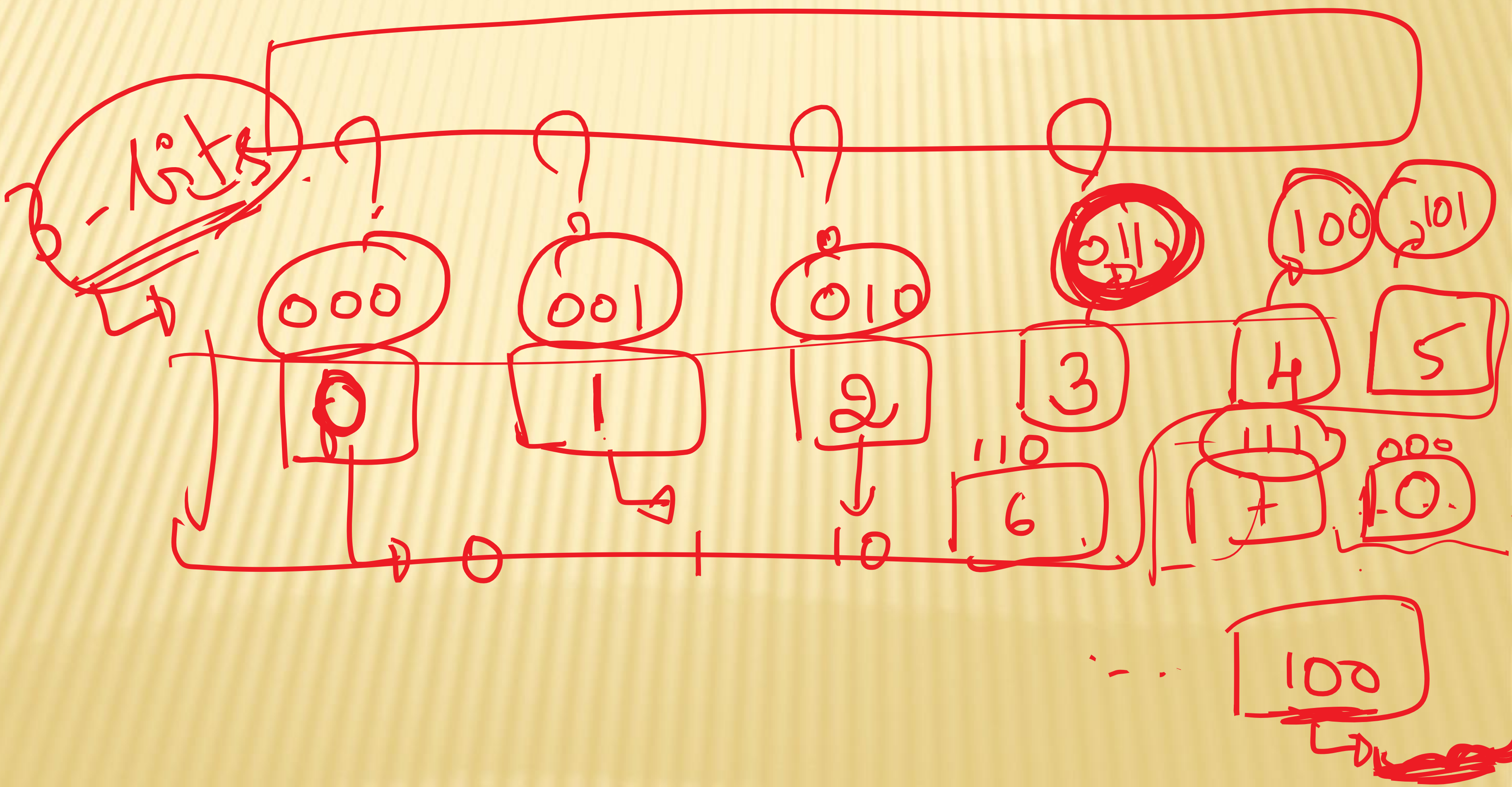
N(S)
N(R)

Send
Receive

7-bits



(d) 16-bit control field format



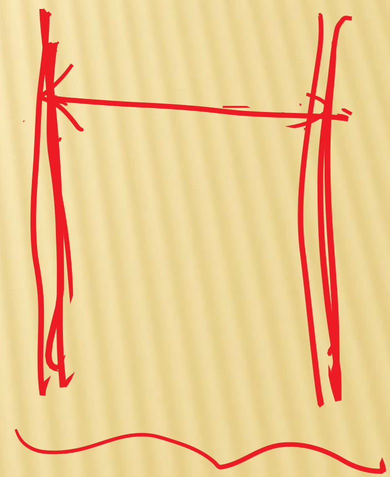
000
001
010
011
100
101
0
1
2
3
4
5
6
7
110
111
100

INFORMATION & FCS FIELDS

- Information Field
  - in information and some unnumbered frames
  - must contain integral number of octets
  - variable length
- Frame Check Sequence Field (FCS)
  - used for error detection
  - either 16 bit CRC or 32 bit CRC

HDLC OPERATION

- consists of exchange of information, supervisory and unnumbered frames
- have three phases
  - initialization
    - by either side, set mode & seq
  - data transfer
    - with flow and error control
    - using both I & S-frames (RR, RNR, REJ, SREJ)
  - disconnect
    - when requested or fault noted



Name	Command/ Response	Description
Information (I)	C/R	Exchange user data
Supervisory (S)		
Receive ready (RR)	C/R	Positive acknowledgment; ready to receive I-frame
Receive not ready (RNR)	C/R	Positive acknowledgment; not ready to receive
Reject (REJ)	C/R	Negative acknowledgment; go back N
Selective reject (SREJ)	C/R	Negative acknowledgment; selective reject
Unnumbered (U)		
Set normal response/extended mode (SNRM/SNRME)	C	Set mode; extended = 7-bit sequence numbers
Set asynchronous response/extended mode (SARM/SARME)	C	Set mode; extended = 7-bit sequence numbers
Set asynchronous balanced/extended mode (SABM, SABME)	C	Set mode; extended = 7-bit sequence numbers
Set initialization mode (SIM)	C	Initialize link control functions in addressed station
Disconnect (DISC)	C	Terminate logical link connection
Unnumbered Acknowledgment (UA)	R	Acknowledge acceptance of one of the set-mode commands
Disconnected mode (DM)	R	Responder is in disconnected mode
Request disconnect (RD)	R	Request for DISC command
Request initialization mode (RIM)	R	Initialization needed; request for SIM command
Unnumbered information (UI)	C/R	Used to exchange control information
Unnumbered poll (UP)	C	Used to solicit control information
Reset (RSET)	C	Used for recovery; resets N(R), N(S)
Exchange identification (XID)	C/R	Used to request/report status
Test (TEST)	C/R	Exchange identical information fields for testing
Frame reject (FRMR)	R	Report receipt of unacceptable frame

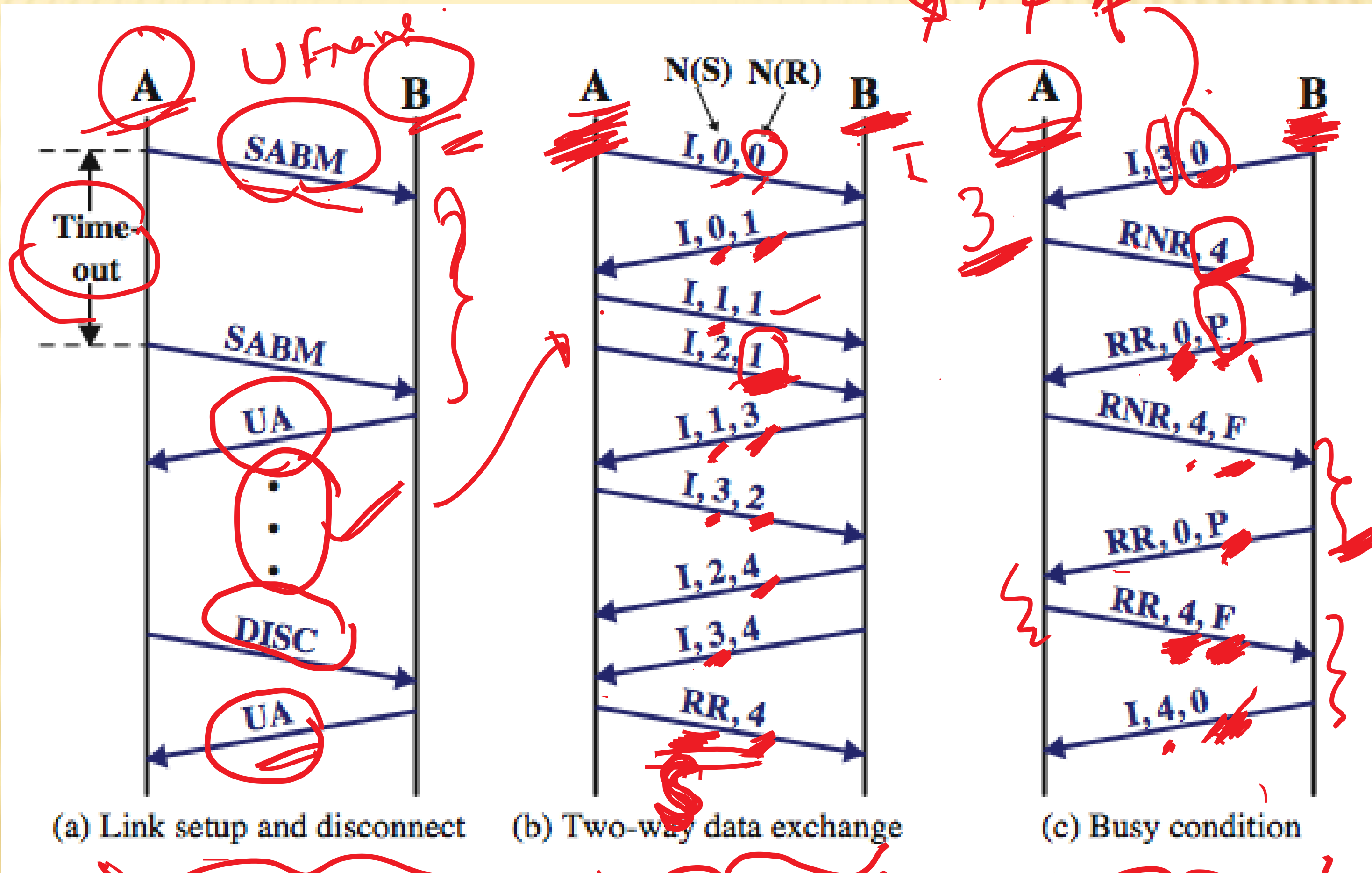
HDLC OPERATION EXAMPLE

(I, 0, 0)

(I, 0, 0)

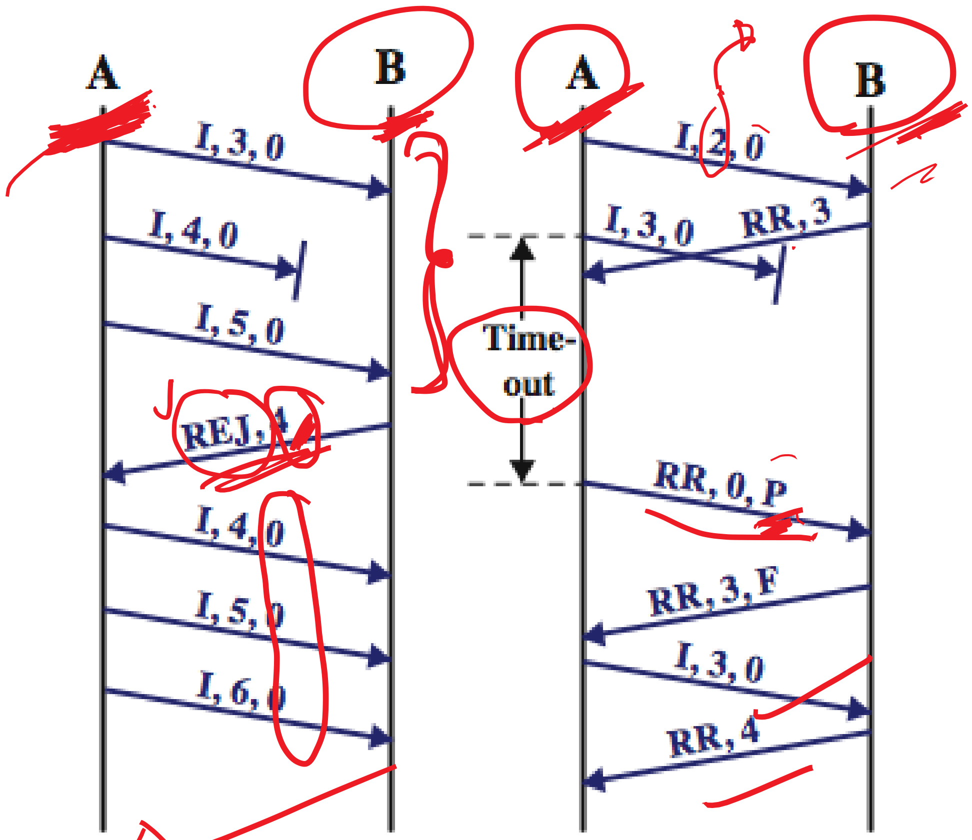
RR
RNR
REJ
SREJ

U frame



I, S

HDLC OPERATION EXAMPLE



(d) Reject recovery

(e) Timeout recovery