Computer Communication Networks

Chapter 3: Data Link Layer

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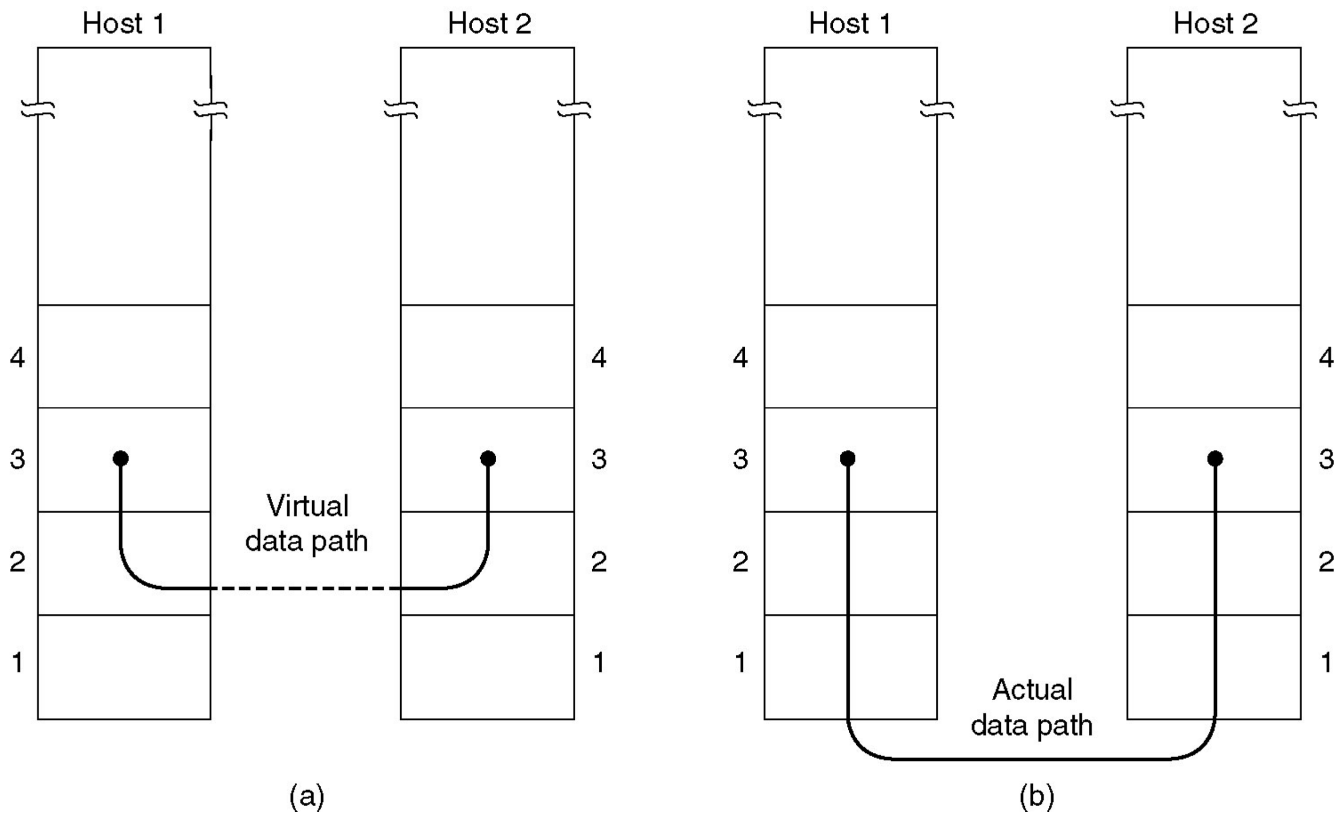
Outline

- Protocol Stack
  - Relation to network and physical layers
  - Sub-layers $\begin{cases} \text{Logical Link Control Layer} \\ \text{Medium Access Control Layer} \end{cases}$
- Logical Link Control Functions
  - Framing
  - Error control
  - Flow control
  - Multiplexing
  - Link Maintenance
  - Security: Authentication & Encryption
  - Link layer switching and bridging
- Medium Access Control Function
  - *Chapter 4*

Protocol Stack
of the Data Link Layer

Protocol Stack of the Data Link Layer

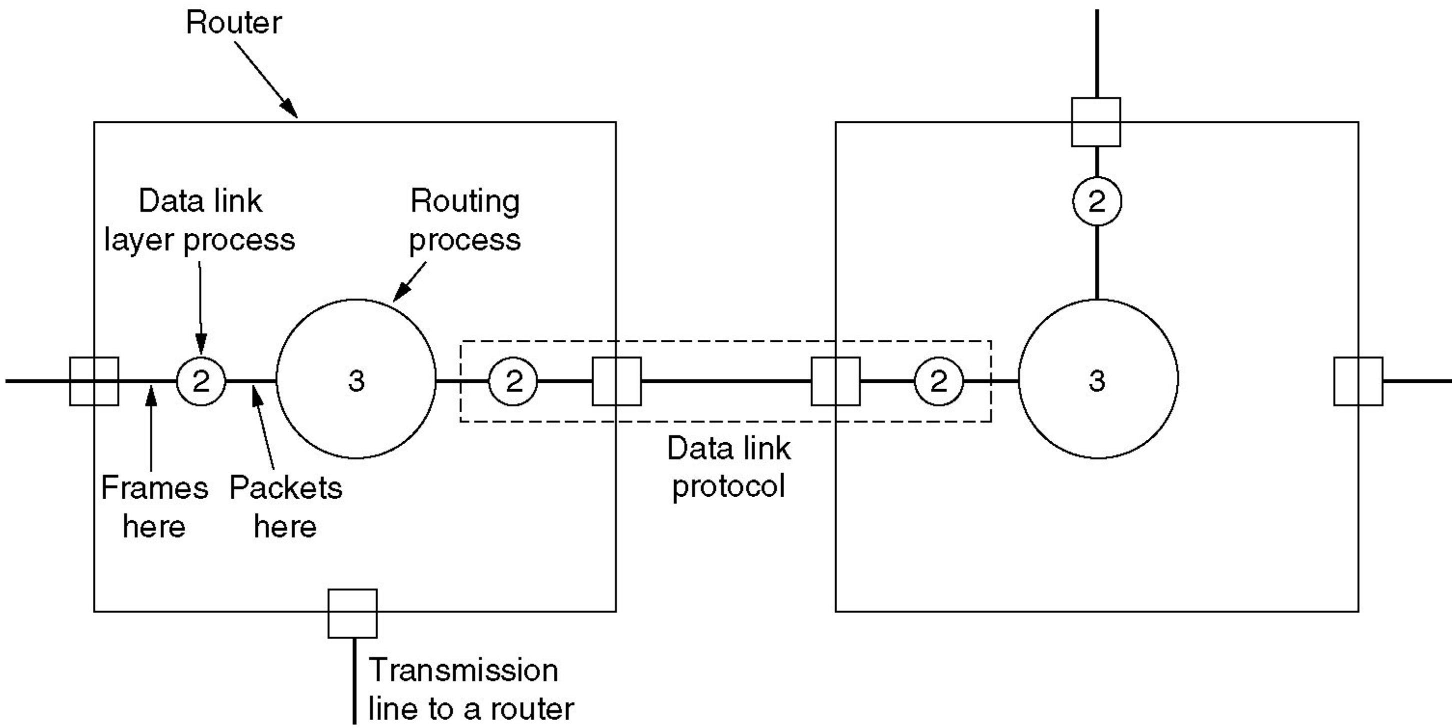


- (a) Virtual communication
- (b) Actual communication

End-to-End vs. Hop-by-Hop

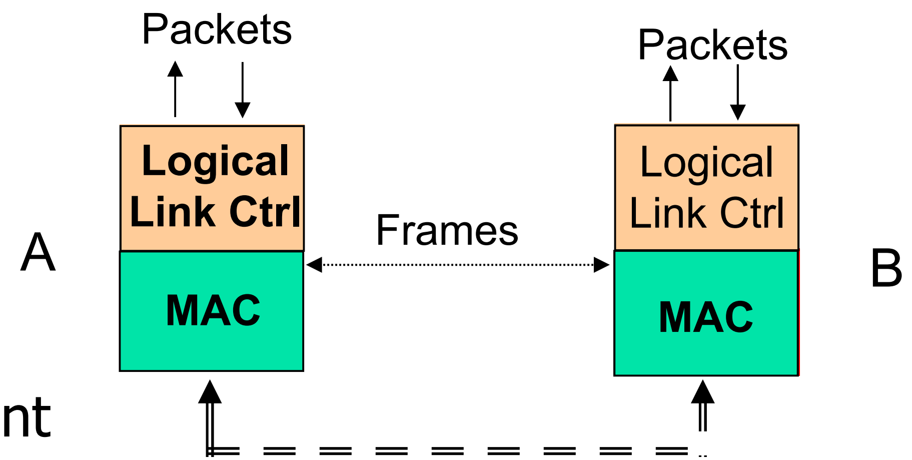
- A service feature can be provided by implementing a protocol
  - end-to-end across the network
  - across every hop in the network
- Example:
  - Perform error control at every hop in the network or only between the source and destination?
  - Perform flow control between every hop in the network or only between source & destination?
- *Usually data link layer is a hop-by-hop approach*

Placement of the Data Link Protocol



Sub-Layers and Functions of the Data Link Layer

- Sub-Layers
  - Logical Link Control
  - Medium Access Contro
- Applications
  - Direct Links or point to point
    - No MAC
  - Broadcast: LANs, wireless
- Features
  - Losses & errors, but no out-of-sequence frames
  - Service types
    - unacknowledged connectionless
    - acknowledged connectionless
    - unacknowledged connection



Functions of the Data Link Upper Layer

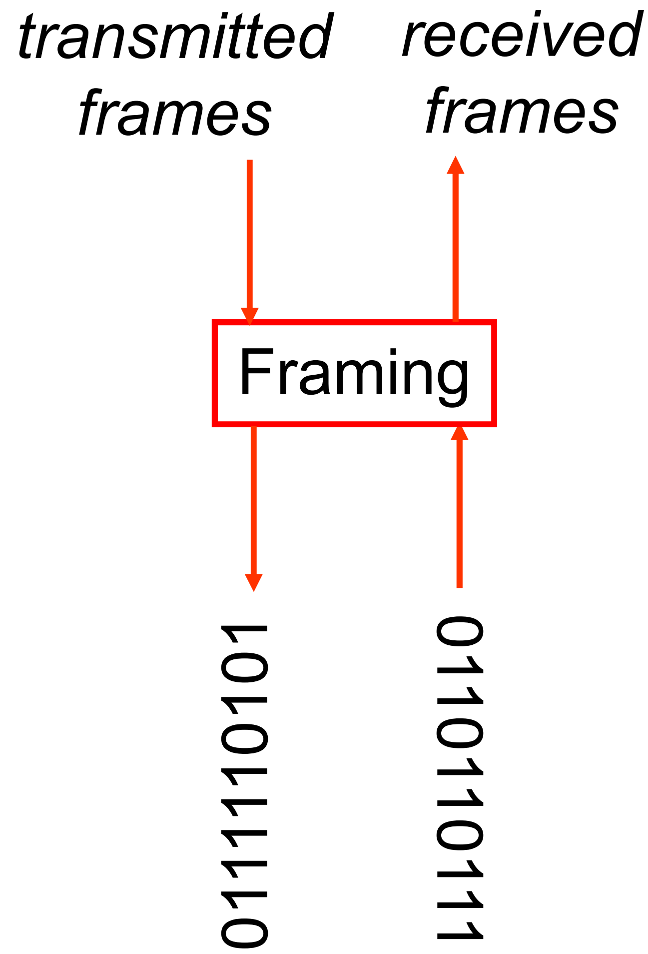
- Provide Services to the Network Layer
  - Framing
  - Error control
  - Flow control
  - Multiplexing
  - Link maintenance
  - Timing recovery
  - Security: Authentication & Encryption

important

Framing
in the Data Link Layer

Framing

- Mapping stream of physical layer bits into frames
- Mapping frames into bit stream
- Frame boundaries can be determined using:
  - Character Counts
  - Control Characters
  - Flags
  - CRC Checks
  - Other fields



Character-Oriented Framing

- Frames consist of integer number of bytes
  - Asynchronous transmission systems using ASCII to transmit printable characters
  - Octets with HEX value <20 are nonprintable
- Special 8-bit patterns used as control characters
  - STX (start of text) = 0x02; ETX (end of text) = 0x03;
- Byte used to carry non-printable characters in frame
  - DLE (data link escape) = 0x10
  - DLE STX (DLE ETX) used to indicate beginning (end) of frame
  - Insert extra DLE in front of occurrence of DLE STX (DLE ETX) in frame
  - All DLEs occur in pairs except at frame boundaries

Data to be sent

A	DLE	B	ETX	DLE	STX	E

After stuffing and framing

DLE	STX	A	DLE	DLE	B	ETX	DLE	DLE	STX	E	DLE	ETX

Byte-Stuffing in PPP (1)

- PPP uses similar frame structure as HDLC, except
  - Protocol type field
  - Payload contains an *integer* number of bytes
- PPP uses the same flag, but uses *byte stuffing*
- Problems with PPP byte stuffing
  - Size of frame varies unpredictably due to byte insertion
  - Malicious users can inflate bandwidth by inserting 7D & 7E

Flag 01111110	Address 1111111	Control 00000011	Protocol	Information	CRC	Flag 01111110

integer # of bytes

All stations are to accept the frame

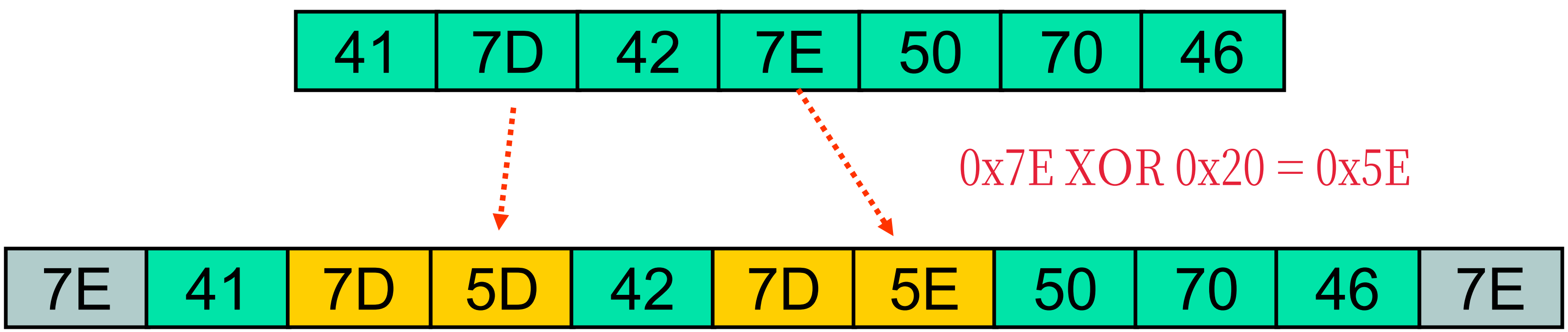
Unnumbered frame

Specifies what kind of packet is contained in the payload, e.g., LCP, NCP, IP, OSI CLNP, IPX

Byte-Stuffing in PPP (2)

- PPP is character-oriented version of HDLC
- Flag is 0x7E (01111110)
- Control escape 0x7D (01111101)
- Any occurrence of flag or control escape inside of frame is replaced with 0x7D followed by original octet XORed with 0x20 (00100000)

Data to be sent



After stuffing and framing

Framing & Bit Stuffing

- Frame delineated by flag character
- HDLC uses *bit stuffing* to prevent occurrence of flag 01111110 inside the frame
- Transmitter inserts extra 0 after each consecutive five 1s *inside* the frame
- Receiver checks for five consecutive 1s
  - if next bit = 0, it is removed
  - if next two bits are 10, then flag is detected
  - If next two bits are 11, then frame has errors

HDLC frame

Flag	Address	Control	Information	FCS	Flag

any number of bits

Example: Bit stuffing & de-stuffing

(a) Data to be sent

0110111111111100

After stuffing and framing

01111110 01101111101111100 *01111110*

(b) Data received

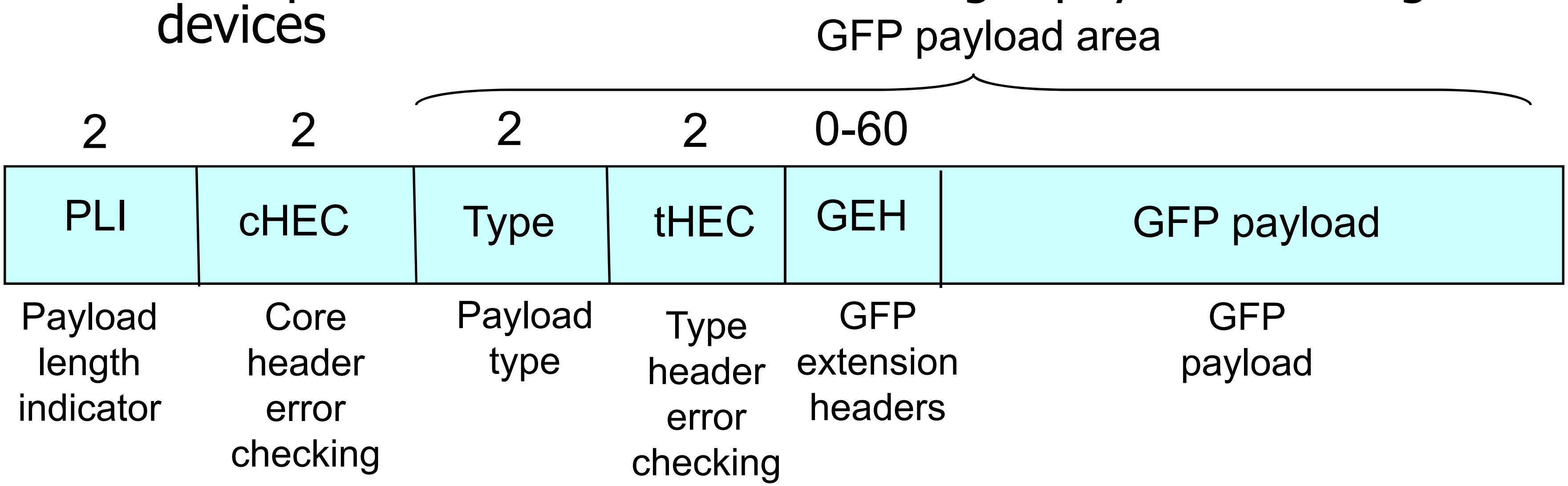
01111110000111011111011111011001111110

After destuffing and deframing

000111011111-11111-110

Generic Framing Procedure

- GFP combines frame length indication with CRC
  - PLI indicated length of frame, then simply count characters
  - cHEC (CRC-16) protects against errors in count field (single-bit error correction + error detection)
- GFP designed to operate over octet-synchronous physical layers (e.g. SONET)
  - Frame-mapped mode for variable-length payloads: Ethernet
  - Transparent mode carries fixed-length payload: storage devices



GFP Synchronization & Scrambling

- Synchronization in three-states
  - *Hunt state*: examine 4-bytes to see if CRC ok
    - If no, move forward by one-byte
    - If yes, move to pre-sync state
  - *Pre-sync state*: tentative PLI indicates next frame
    - If N successful frame detections, move to sync state
    - If no match, go to hunt state
  - *Sync state*: normal state
    - Validate PLI/cHEC, extract payload, go to next frame
    - Use single-error correction
    - Go to hunt state if non-correctable error
- Scrambling
  - Payload is scrambled to prevent malicious users from inserting long strings of 0s which cause SONET equipment to lose bit clock synchronization

Error Control in the Data Link Layer (ARQ)

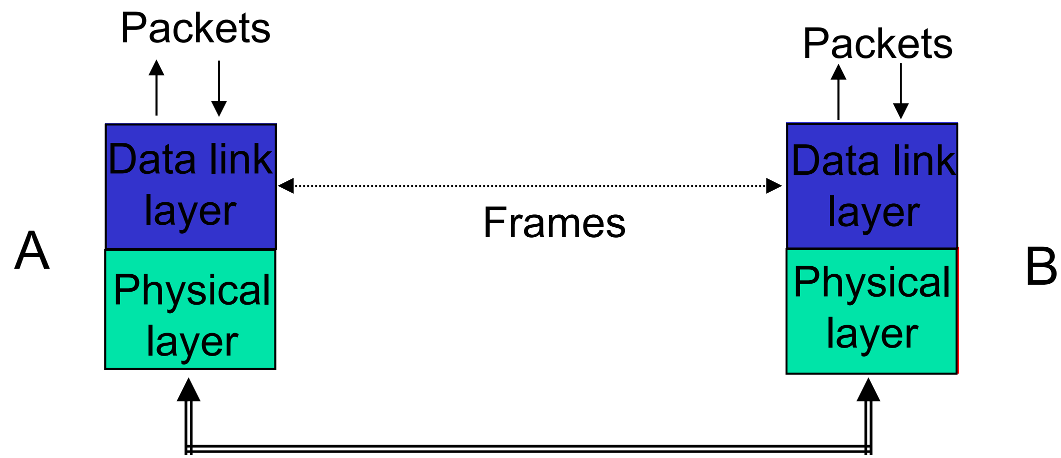
Error Control

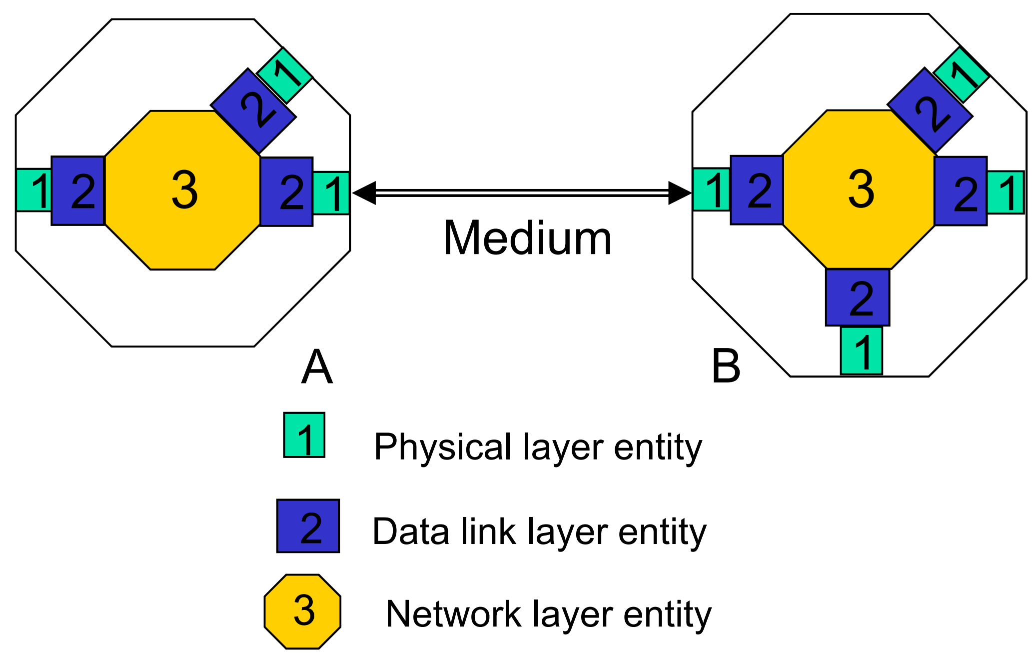
*usually used only in the physical layer

- FEC Forward Error Correction
  - Data link FEC versus physical link FEC
- ARQ Auto Repeat Request
  - Retransmission after error detection
  - Simplex Stop-and-Wait protocol
  - Sliding window protocol
    - One-bit sliding window
    - Go-back-N ARQ
    - Selective repeat ARQ

Error control in Data Link Layer

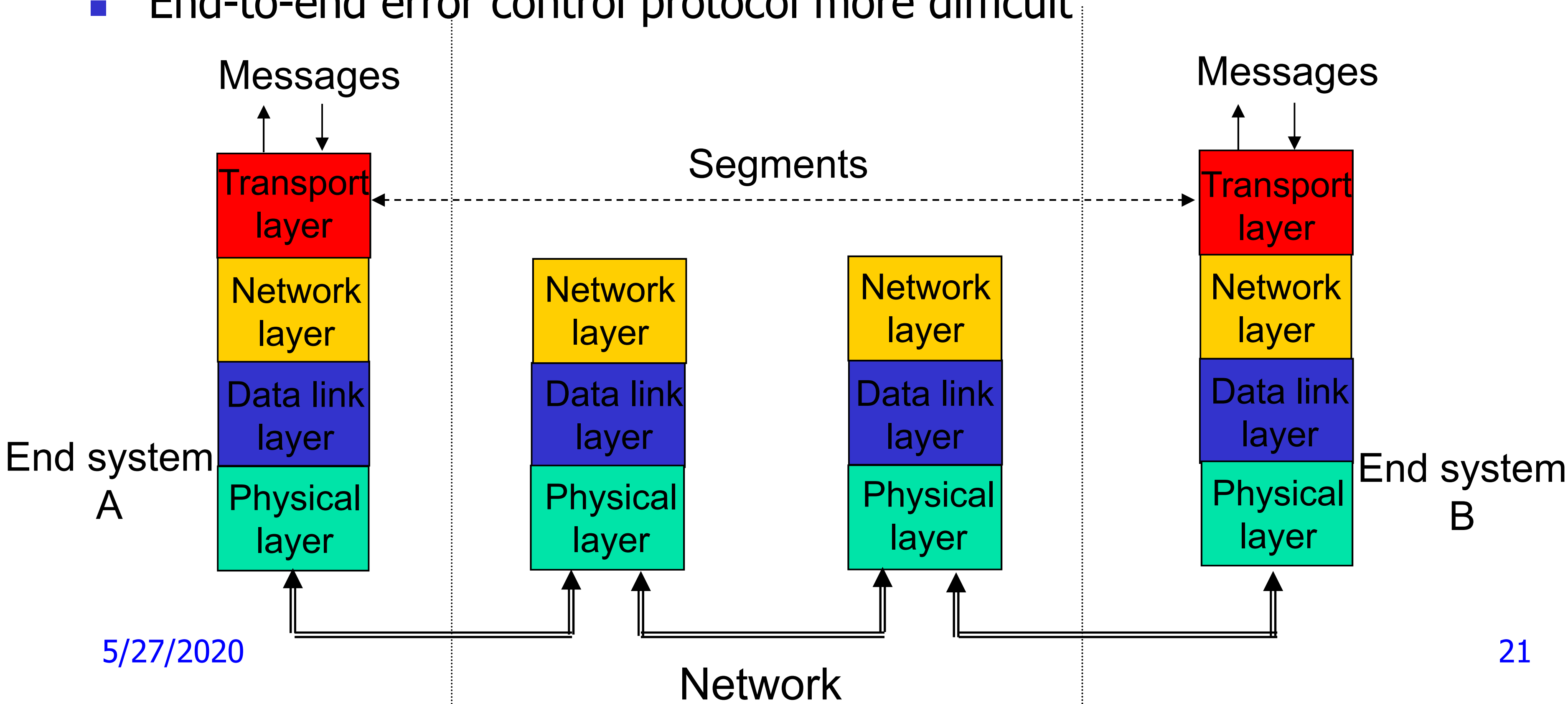
- Data Link operates over wire-like, directly-connected systems
- Frames can be corrupted or lost, but arrive in order
- Data link performs error-checking & retransmission
- Ensures error-free packet transfer between two systems





Error Control in Transport Layer

- Transport layer protocol (e.g. TCP) sends segments across network and performs end-to-end error checking & retransmission
- Underlying network is assumed to be unreliable
- Segments can experience long delays, can be lost, or arrive out-of-order because packets can follow different paths across network
- End-to-end error control protocol more difficult

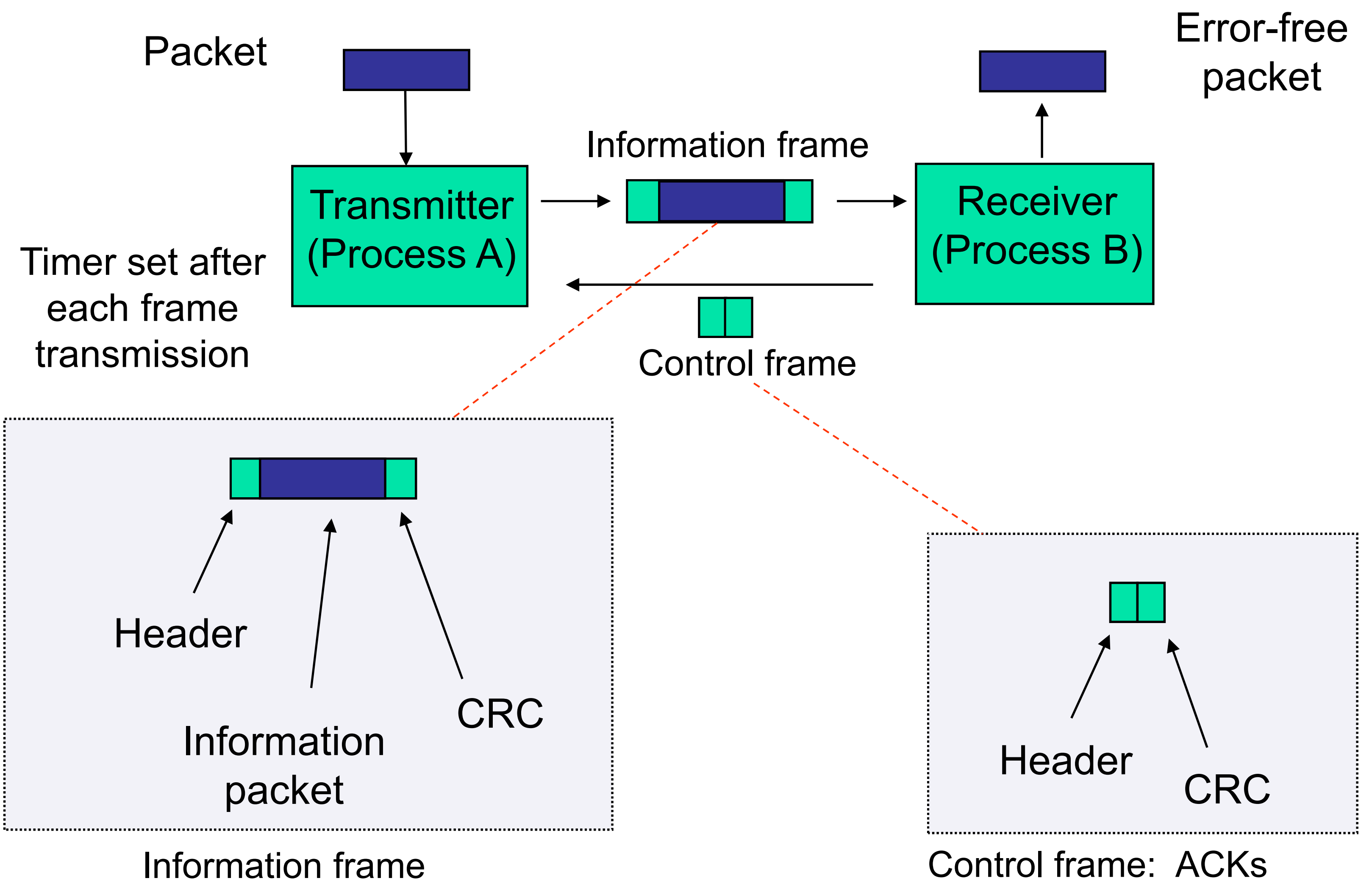


Automatic Repeat Request (ARQ)

- *Purpose*: to ensure a sequence of information packets is delivered in order and without errors or duplications despite transmission errors & losses
- We will look at:
  - Stop-and-Wait ARQ
  - Go-Back N ARQ
  - Selective Repeat ARQ
- Basic elements of ARQ:
  - *Error-detecting code* with high error coverage
  - *ACKs* (positive acknowledgments)
  - *NAKs* (negative acknowlegments)
  - *Timeout mechanism*

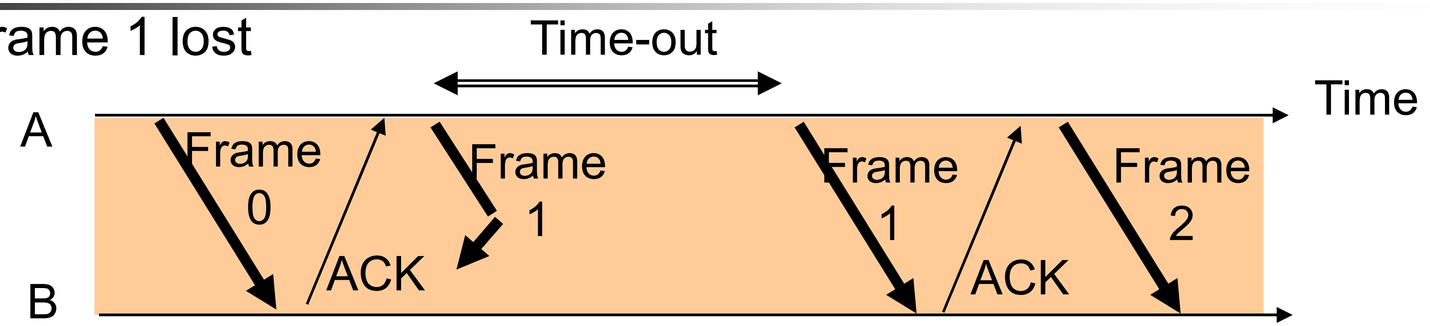
Stop-and-Wait ARQ

Transmit a frame, wait for ACK

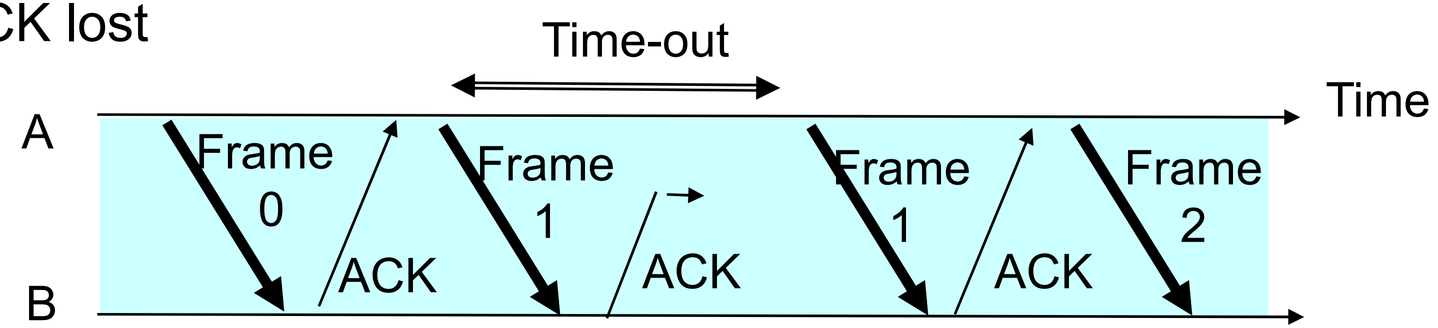


Need of Sequence Numbers (case 1)

(a) Frame 1 lost



(b) ACK lost

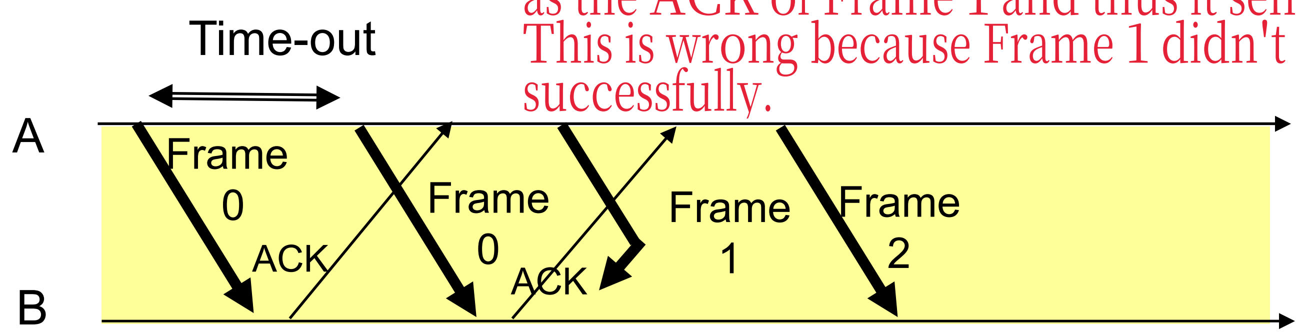


- In cases (a) & (b) the transmitting station A acts the same way
- But in case (b) the receiving station B accepts frame 1 twice
- Question: How does the receiver know the second frame is also frame 1?
- Answer: ***Add frame sequence number in header***
- S_{last} is sequence number of most recent transmitted frame

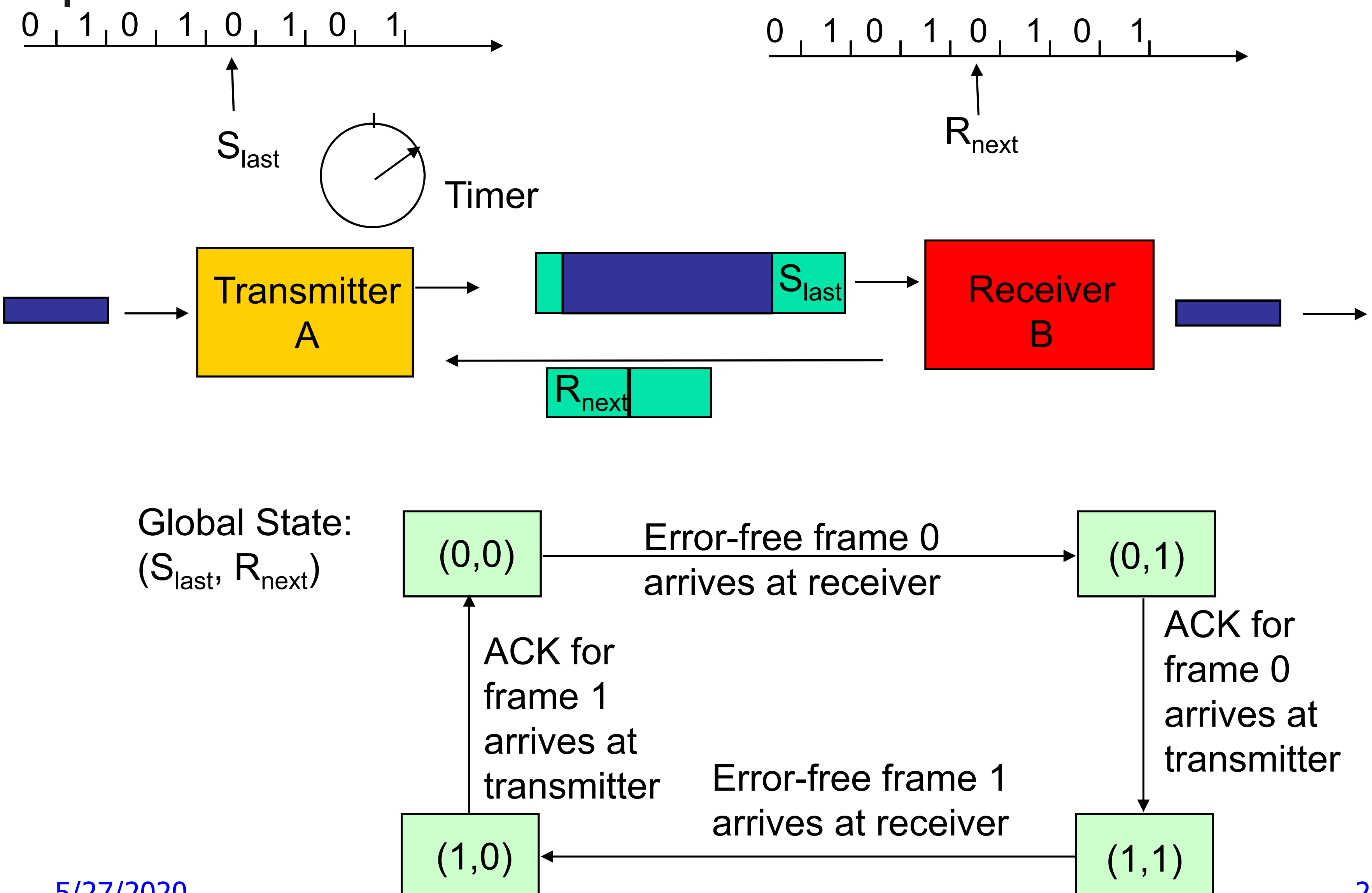
Need of Sequence number (case 2)

- The transmitting station A misinterprets duplicate ACKs
- Incorrectly assumes second ACK acknowledges Frame 1
- Question: How can the receiver know the second ACK is for frame 0?
- Answer: ***Add frame sequence number in ACK header***
- R_{next} is sequence number of next frame expected by the receiver
- Implicitly acknowledges receipt of all prior frames

In this case, A mistaken the second ACK of Frame 0 as the ACK of Frame 1 and thus it sent out Frame 2. This is wrong because Frame 1 didn't arrive at B successfully.



1-Bit Sequence Numbering Suffices



Mechanisms of Stop-and-Wait ARQ

Transmitter

Ready state

- Await request from higher layer for packet transfer
- When request arrives, transmit frame with updated S_{last} and CRC
- Go to Wait State

Wait state

- Wait for ACK or timer to expire; block requests from higher layer
- If timeout expires
  - retransmit frame and reset timer
- If ACK received:
  - If sequence number is incorrect or if errors detected: ignore ACK
  - If sequence number is correct ($R_{next} = S_{last} + 1$): accept frame, update S_{last} ($S_{last}=R_{next}$), and go to Ready state

Receiver

Always in Ready State

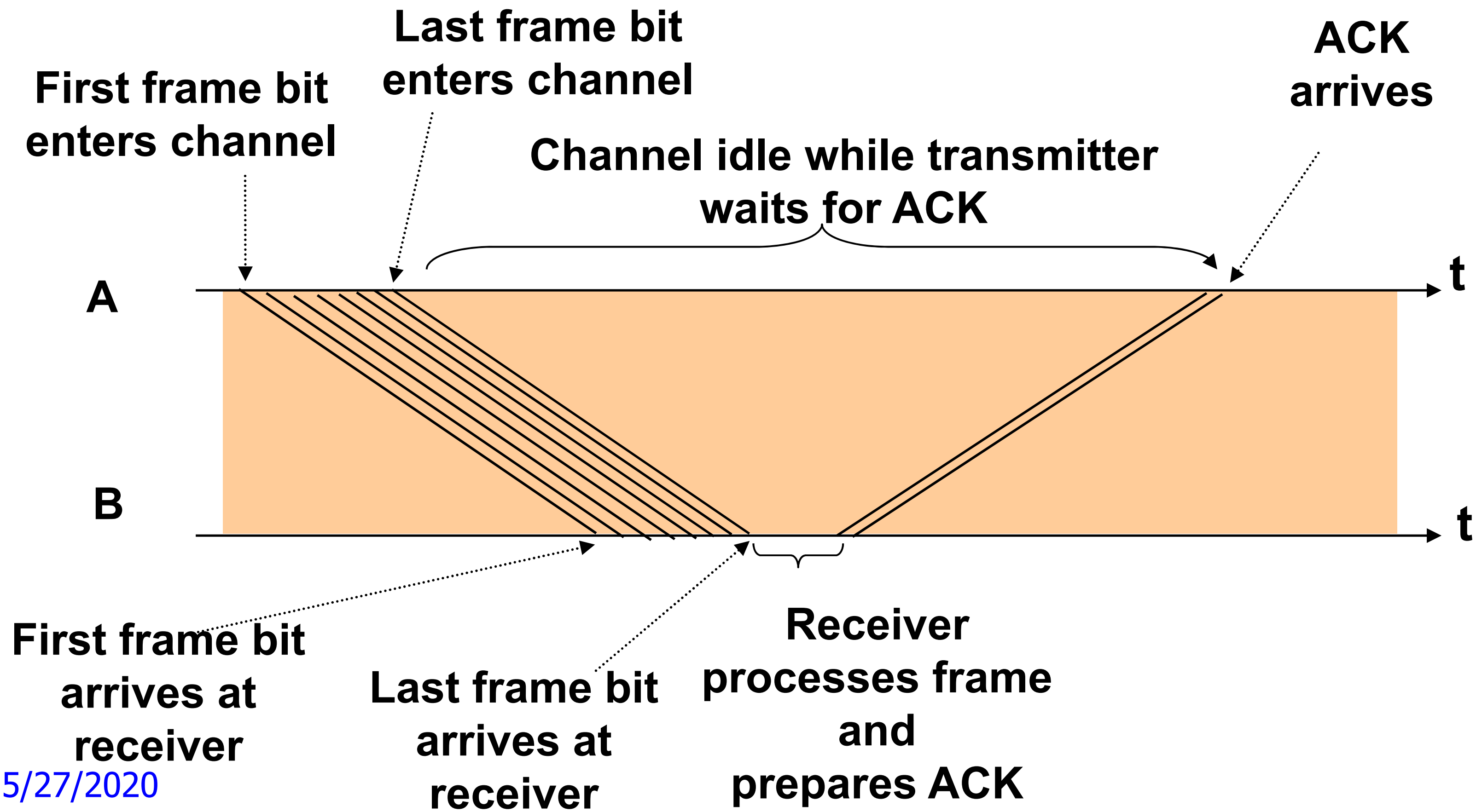
- Wait for arrival of new frame
- When frame arrives, check for errors
- If no errors detected and sequence number is correct ($S_{last}=R_{next}$), then
  - accept frame,
  - update R_{next},
  - send ACK frame with R_{next},
  - deliver packet to higher layer
- If no errors detected and wrong sequence number
  - discard frame
  - send ACK frame with R_{next}
- If errors detected
  - discard frame

Applications of Stop-and-Wait ARQ

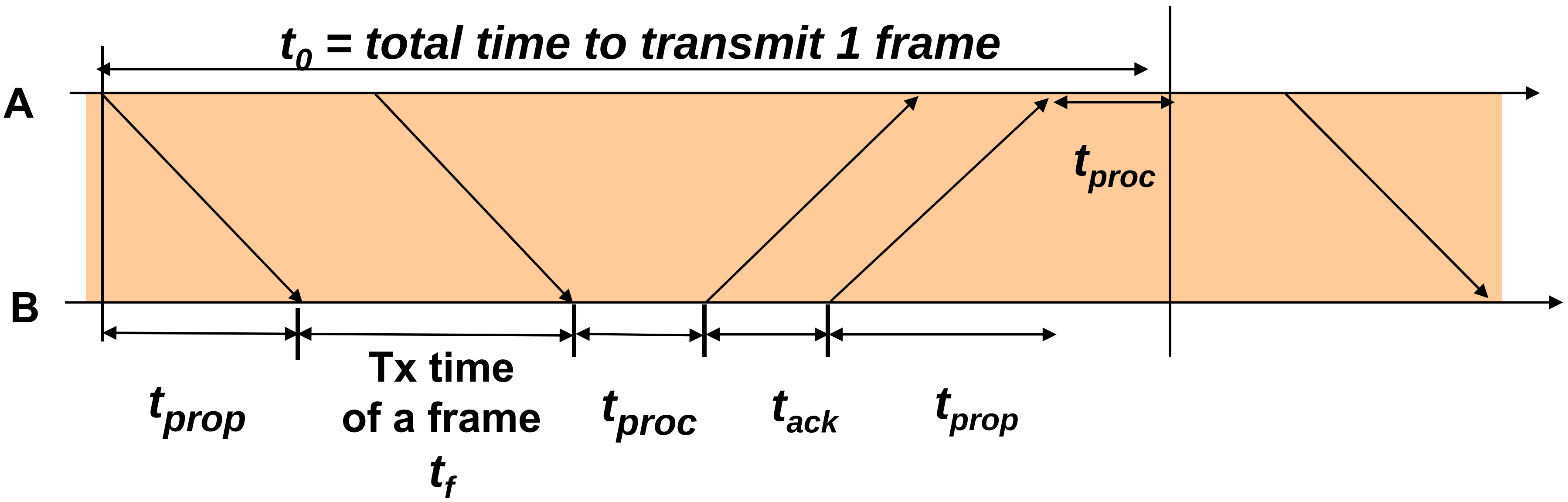
- IBM *Binary Synchronous Communications protocol* (Bisync): character-oriented data link control
- *Xmodem*: modem file transfer protocol
- *Trivial File Transfer Protocol* (RFC 1350): simple protocol for file transfer over UDP
- 802.11 CSMA/CA (part of collision avoidance)

Efficiency of Stop-and-Wait

- 10000 bit frame @ 1 Mbps takes 10 ms to transmit
- If wait for ACK = 1 ms, then efficiency = 10/11= 91%
- If wait for ACK = 20 ms, then efficiency =10/30 = 33%



Stop-and-Wait Model



$$t_0 = 2t_{prop} + 2t_{proc} + t_f + t_{ack}$$

$$= 2t_{prop} + 2t_{proc} + \frac{n_f}{R} + \frac{n_a}{R}$$

bits/info frame

bits/ACK frame

transmission rate

Stop-and-Wait Efficiency on Error-free channel

Effective transmission rate:

bits for header & CRC

$$R_{eff}^{0} = \frac{\text{number of information bits delivered to destination}}{\text{total time required to deliver the information bits}} = \frac{n_f - n_o}{t_0},$$

Transmission efficiency:

$$\eta_0 = \frac{R_{eff}}{R} = \frac{\frac{n_f - n_o}{t_0}}{R} = \frac{1 - \frac{n_o}{n_f}}{1 + \frac{n_a}{n_f} + \frac{2(t_{prop} + t_{proc})R}{n_f}}.$$

Effect of frame overhead

Effect of ACK frame

Effect of ***Bandwidth-Delay Product***

Example: Impact of Delay-Bandwidth Product

n_f=1250 bytes = 10000 bits, n_a=n_o=25 bytes = 200 bits

Efficiency / Bandwidth \ Delay	1 ms 200 km	10 ms 2000 km	100 ms 20000 km	1 sec 200000 km
1 Mbps	10^3 88%	10^4 49%	10^5 9%	10^6 1%
1 Gbps	10^6 1%	10^7 0.1%	10^8 0.01%	10^9 0.001%

Stop-and-Wait does not work well for very high speeds or long propagation delays

If Bandwidth-Delay Product of the system is high, don't use Stop-and-Wait.

Stop-and-Wait Efficiency in Channel with Errors

- Let $1 - P_f$ = probability that a frame arrives w/o errors
without
- Avg. # of transmissions to achieve the first correct arrival is then $1/(1-P_f)$
- "If 1-in-10 get through without error, then avg. 10 tries to success" – how to use probability to derive?
- Avg. Total Time per frame is then $t_0/(1 - P_f)$

$$\eta_{SW} = \frac{R_{eff}}{R} = \frac{\dfrac{n_f - n_o}{t_0 \big/ 1 - P_f}}{R} = \frac{1 - \dfrac{n_o}{n_f}}{1 + \dfrac{n_a}{n_f} + \dfrac{2(t_{prop} + t_{proc})R}{n_f}}(1 - P_f)$$

Effect of frame loss

Example: Impact of Bit Error Rate

n_f=1250 bytes = 10000 bits, n_a=n_o=25 bytes = 200 bits

Find efficiency for random bit errors with p=0, 10^{-6}, 10^{-5}, 10^{-4}

$$1 - P_f = (1-p)^{n_f} \approx e^{-n_f p} \quad \text{for large } n_f \text{ and small } p$$

Bandwidth: 1 Mbps & Delay: 1 ms

Bit error	0	10^{-6}	10^{-5}	10^{-4}
$1 - P_f$ Efficiency	1 88%	0.99 86.6%	0.905 79.2%	0.368 32.2%

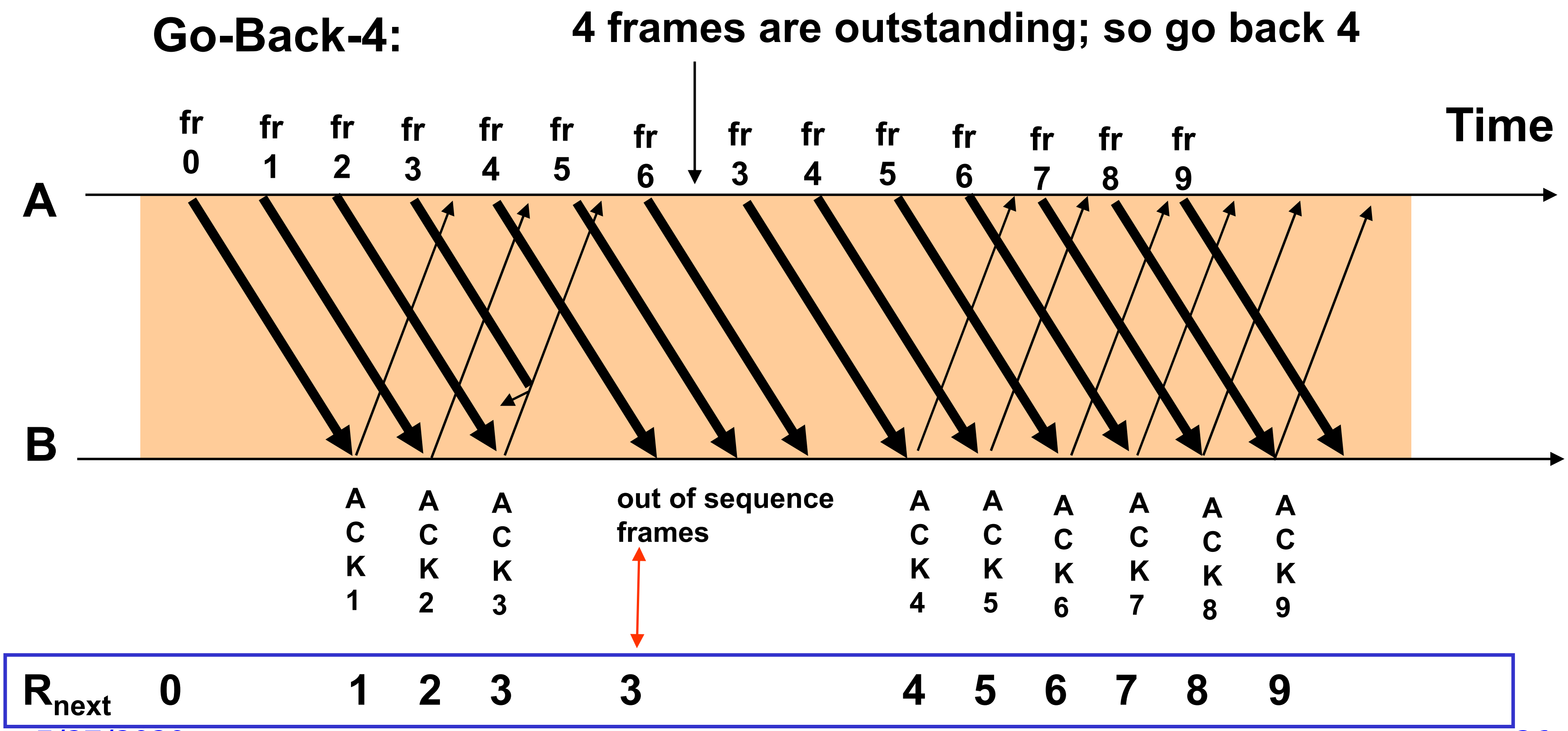
Bit errors impact performance as $n_f p$ approach 1

Go-Back-N

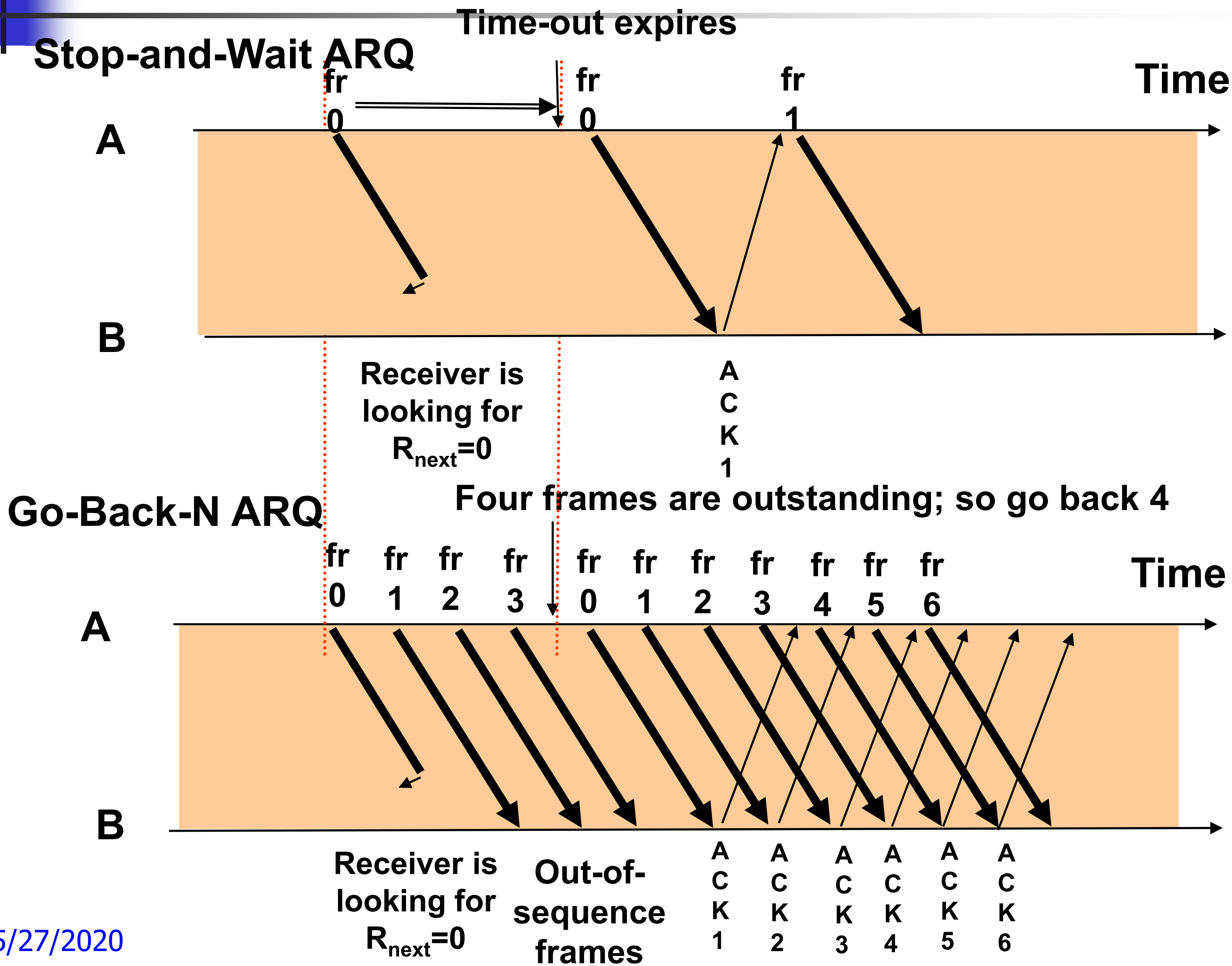
- Improve Stop-and-Wait by not waiting!
- Keep channel busy by continuing to send frames
- Allow a window of up to W_s outstanding frames
- Use *m*-bit sequence numbering
- If ACK for oldest frame arrives before window is exhausted, we can continue transmitting
- If window is exhausted, pull back and retransmit all outstanding frames
- Alternative: Use timeout

Procedures

- Frame transmission are *pipelined* to keep the channel busy
- Frame with errors and subsequent out-of-sequence frames are ignored
- Transmitter is forced to go back when window of 4 is exhausted



Window Size: Round-Trip Time

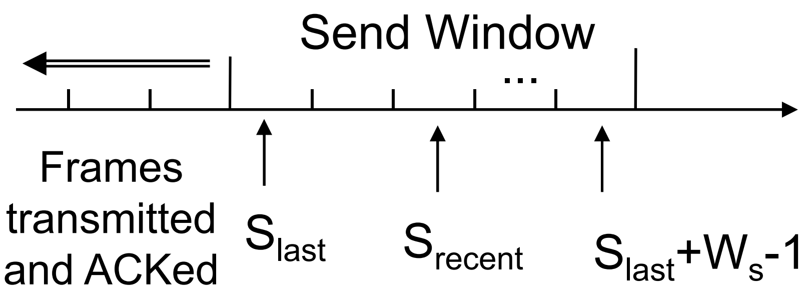


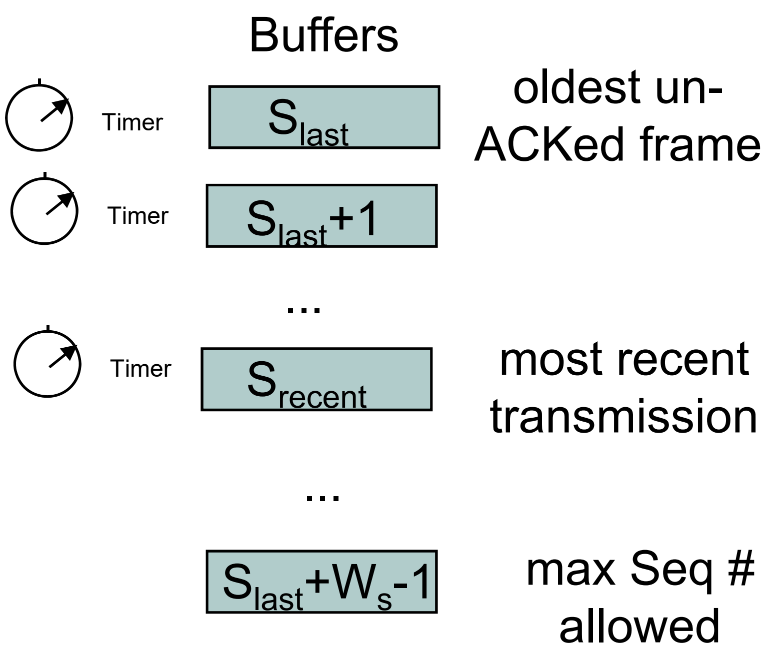
Go-Back-N with Timeout

- Problem with Go-Back-N as presented:
  - If frame is lost and source does not have frame to send, then window will not be exhausted and recovery will not commence
- Use a timeout with each frame
  - When timeout expires, resend all outstanding frames

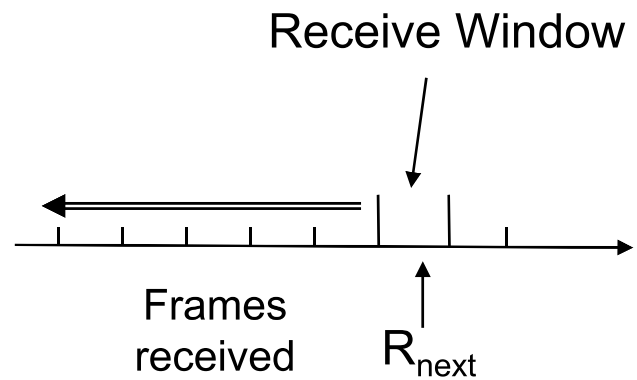
Go-Back-N Transmitter & Receiver

Transmitter





Receiver

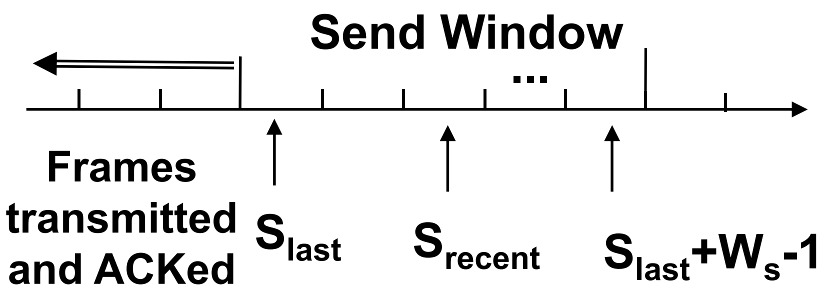


Receiver will only accept a frame that is error-free and that has sequence number R_{next}

When such frame arrives R_{next} is incremented by one, so the *receive window slides forward* by one

Sliding Window Operation

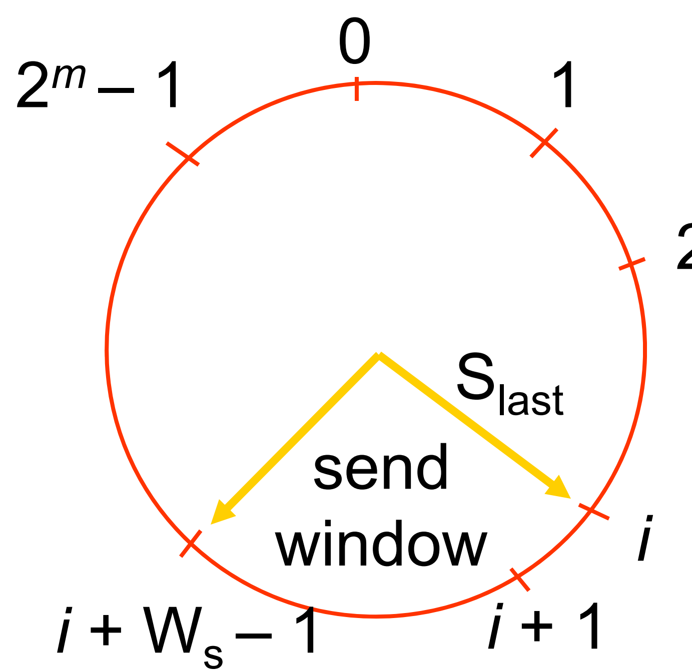
Transmitter



Transmitter waits for error-free ACK frame with sequence number S_{last} (= R_{next}-1)

When such ACK frame arrives, S_{last} is incremented by one, and the *send window slides forward* by one

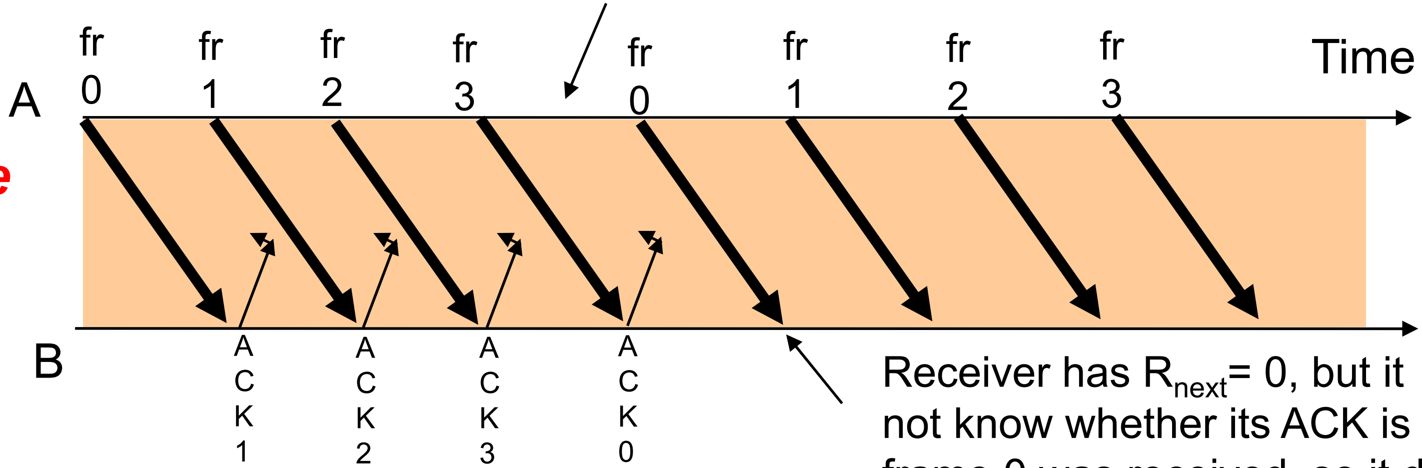
***m*-bit Sequence Numbering**



Examples

$M = 2^2 = 4$, Go-Back - 4: Transmitter goes back 4

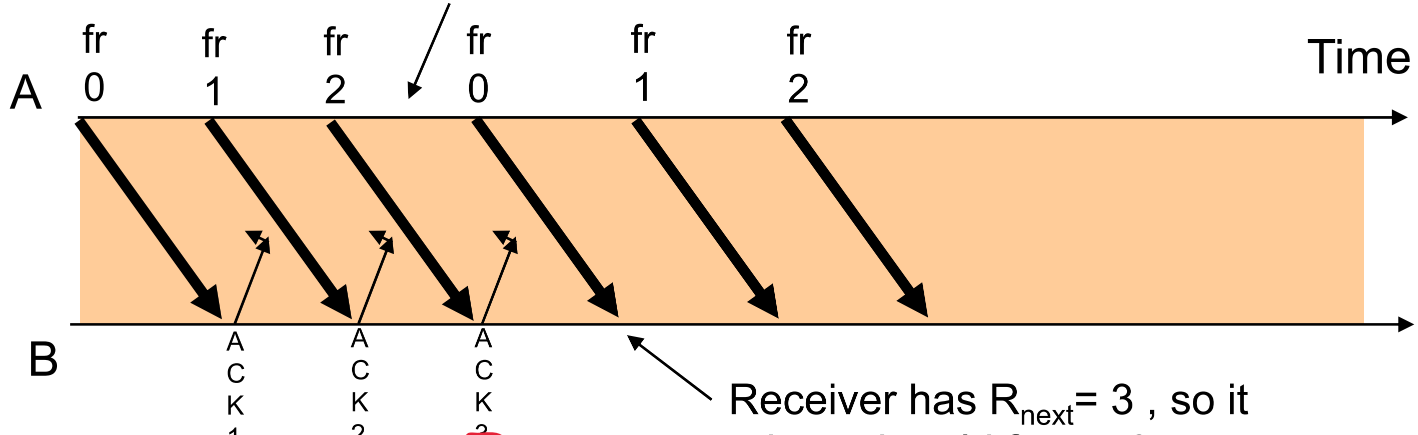
Allowable Window Size
W_s <= 2^m-1



R_{next} 0 1 2 3 0

Receiver has R_{next}= 0, but it does not know whether its ACK is frame 0 was received, so it does not know whether this is the old frame 0 or a new frame 0

$M = 2^2 = 4$, Go-Back-3: Transmitter goes back 3

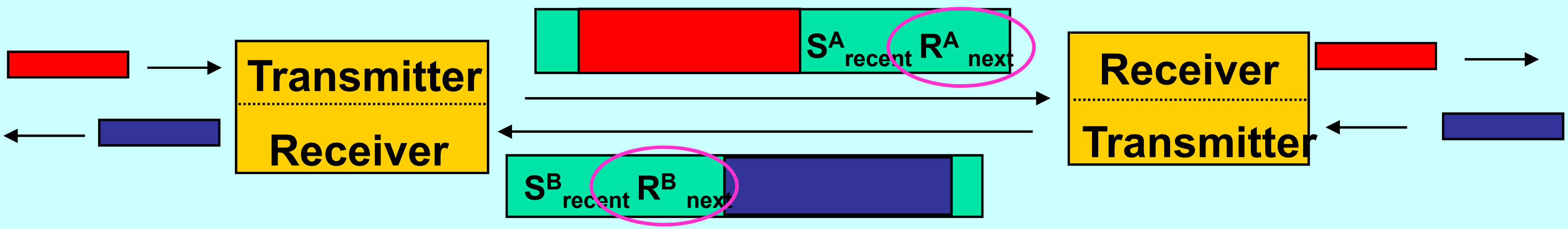


Receiver has R_{next}= 3 , so it rejects the old frame 0

R_{next} 0 1 2 3

为什么不是0？和上面的例子有什么区别？

ACK Piggybacking in Bidirectional GBN



"A" Receive Window

R^A_{next}

"A" Send Window

S^A_{last} $S^A_{last}+W^A_s-1$

Buffers

Timer S^A_{last}

Timer $S^A_{last}+1$

...

Timer S^A_{recent}

...

Timer $S^A_{last}+W^A_s-1$

What's the relationship among the 4 windows?

"B" Receive Window

R^B_{next}

"B" Send Window

S^B_{last} $S^B_{last}+W^B_s-1$

Buffers

Timer S^B_{last}

Timer $S^B_{last}+1$

...

Timer S^B_{recent}

...

Timer $S^B_{last}+W^B_s-1$

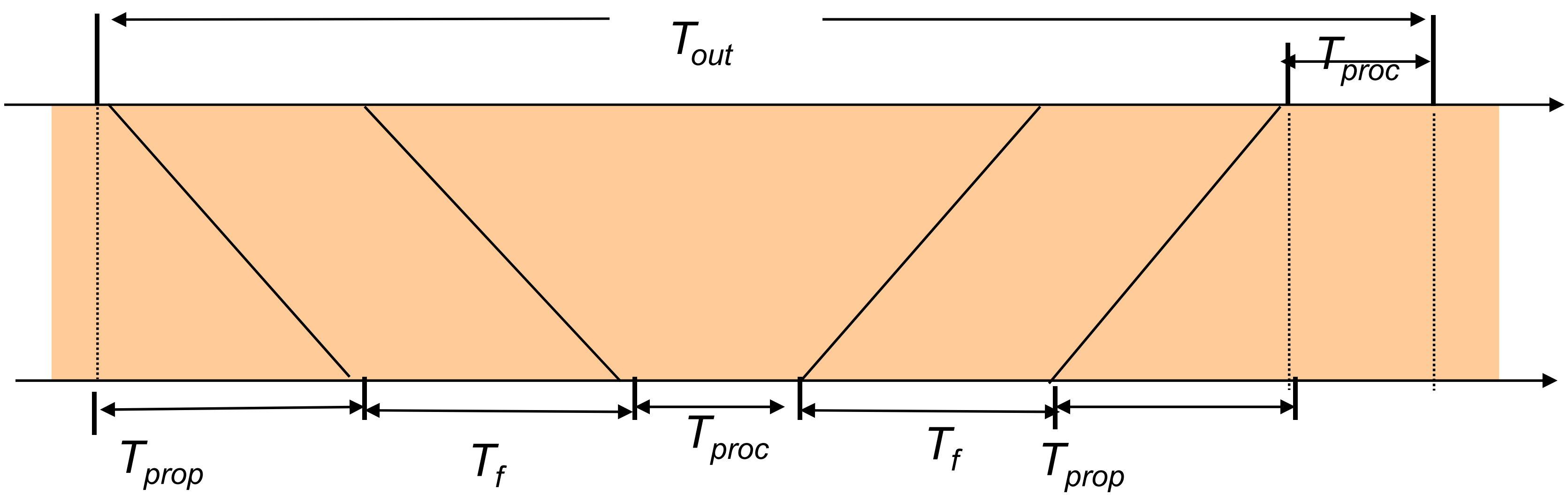
Note: Out-of-sequence error-free frames discarded after R_{next} examined

Applications of Go-Back-N ARQ

- *HDLC* (High-Level Data Link Control): bit-oriented data link control
- *V.42 modem*: error control over telephone modem links
- Upper layers

Required Timeout & Window Size

- Timeout value should allow for:
  - 2 propagation times + 2 processing times: $2\,(T_{prop} + T_{proc})$
  - Transmission time of a frame T_f
  - Transmission time of the next frame carries the ACK, T_f
- W_s should be large enough to keep channel busy for T_{out}



Required Window Size for Bandwidth-Delay Product (BDP)

Frame = 1250 bytes =10,000 bits, R = 1 Mbps		
$2(t_{prop} + t_{proc})$	**2 x Delay x BW**	**Window**
1 ms	1000 bits	1
10 ms	10,000 bits	2 10000/10000+1
100 ms	100,000 bits	11 100000/10000+1
1 second	1,000,000 bits	101 1000000/10000+1

How to derive the window size?

Efficiency of Go-Back-N

- GBN is completely efficient, if W_s large enough to keep channel busy, and if channel is error-free
- However, assuming frame loss probability P_f, then the time to deliver a frame is:
  - t_f if first frame transmission succeeds : $(1 - P_f)$
  - $t_f + W_s t_f/(1-P_f)$ if the first transmission does not succeed: P_f

$$t_{GBN} = t_f(1-P_f) + P_f\{t_f + \frac{W_s t_f}{1-P_f}\} = t_f + P_f \frac{W_s t_f}{1-P_f} \quad \text{and}$$

$$\eta_{GBN} = \frac{\frac{n_f - n_o}{t_{GBN}}}{R} = \frac{1 - \frac{n_o}{n_f}}{1 + (W_s - 1)P_f}(1 - P_f)$$

BDP determines W_s

Example: Bit Error Rate Impact on GBN

n_f=1250 bytes = 10000 bits, n_a=n_o=25 bytes = 200 bits

Compare S&W with GBN efficiency for random bit errors with p = 0, 10^{-6}, 10^{-5}, 10^{-4} and R = 1 Mbps & 100 ms

1 Mbps x 100 ms = 100000 bits = 10 frames ? Use W_s = 11

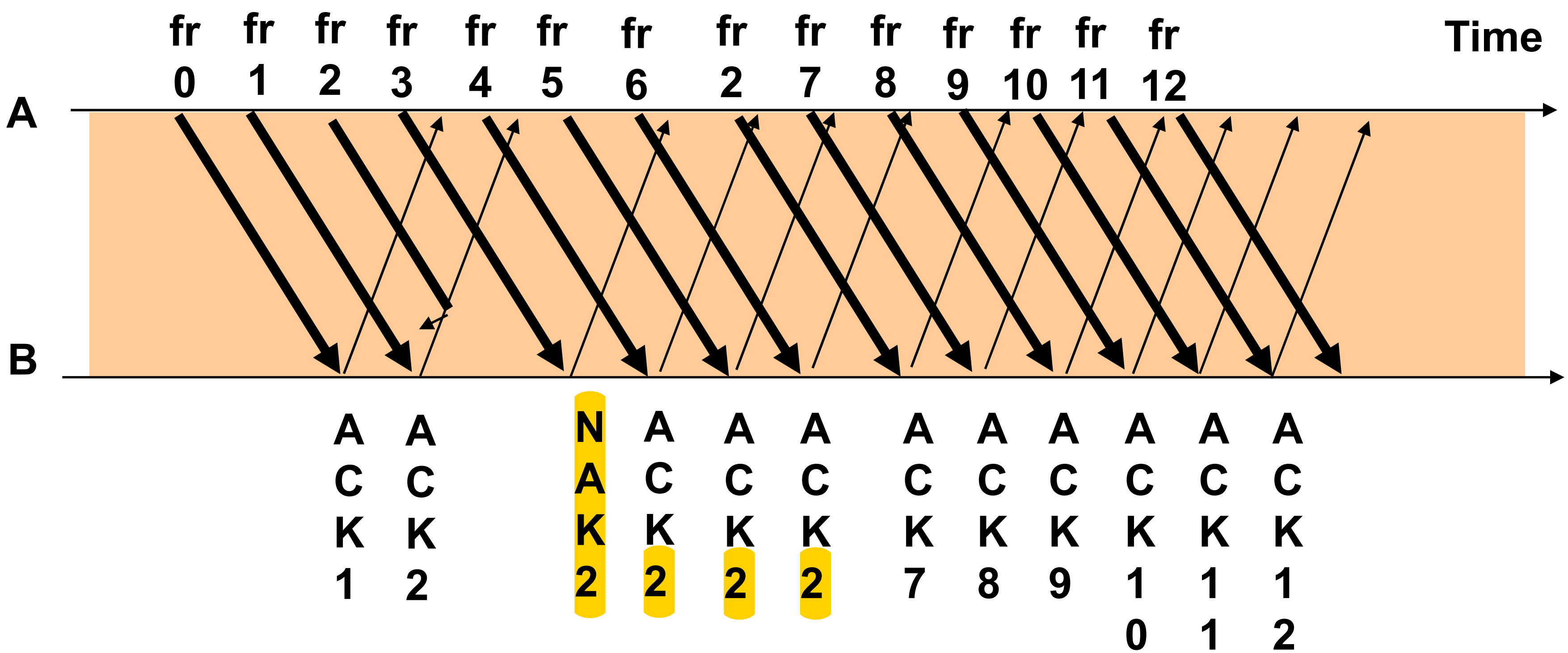
Efficiency p / ARQ	0	10^{-6}	10^{-5}	10^{-4}
S&W	8.9%	8.8%	8.0%	3.3%
GBN	98%	88.2%	45.4%	4.9%

- *Go-Back-N significant improvement over Stop-and-Wait for large delay-bandwidth product*
- *Go-Back-N becomes inefficient as error rate increases*

Selective Repeat ARQ

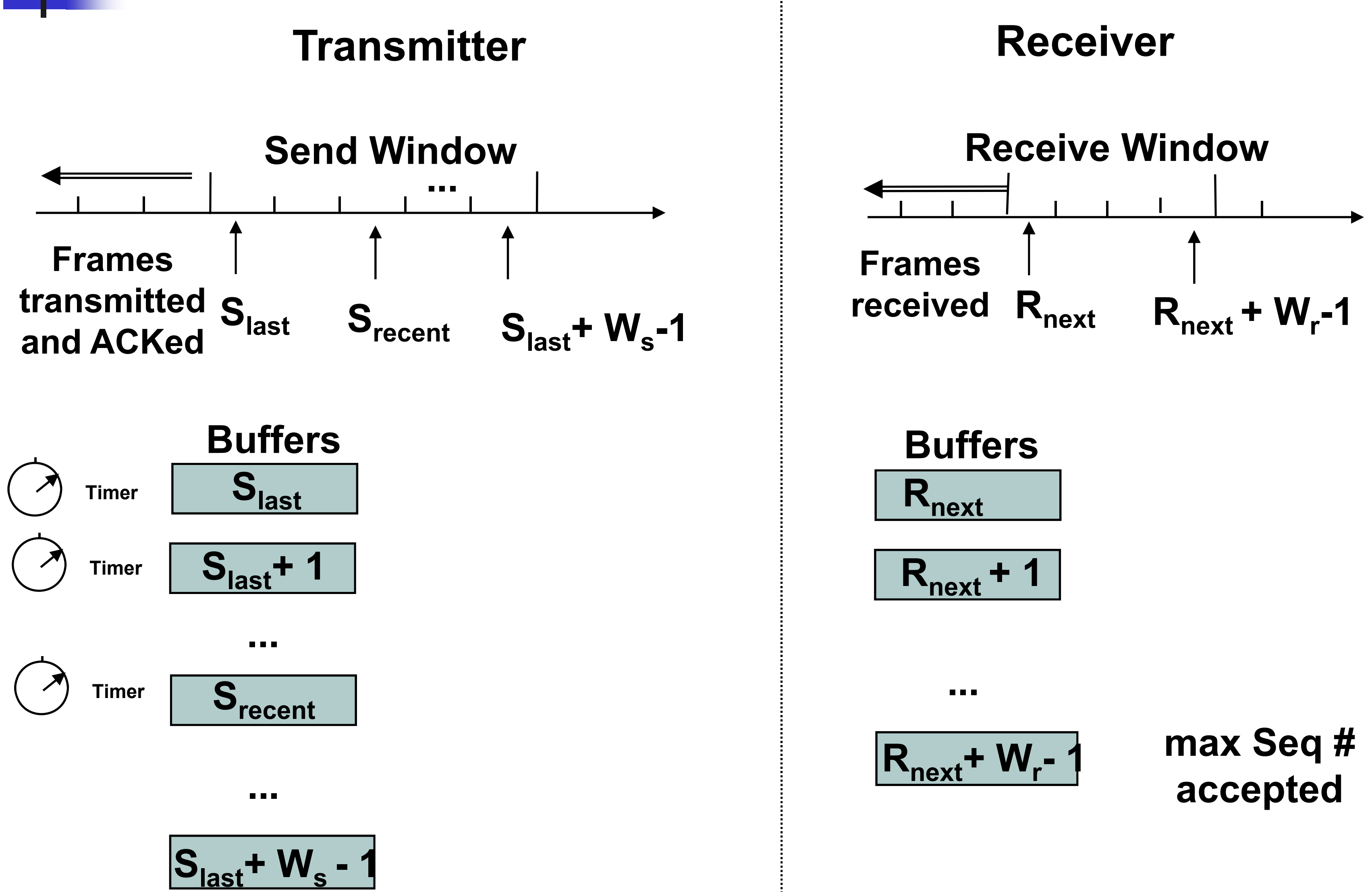
- Go-Back-N ARQ inefficient because *multiple* frames are resent when errors or losses occur
- Selective Repeat retransmits *only an individual frame*
  - Timeout causes individual corresponding frame to be resent
  - NAK causes retransmission of oldest un-acked frame
- Receiver maintains a *receive window* of sequence numbers that can be accepted
  - Error-free, but out-of-sequence frames with sequence numbers within the receive window are buffered
  - Arrival of frame with R_{next} causes window to slide forward by 1 or more

Mechanism



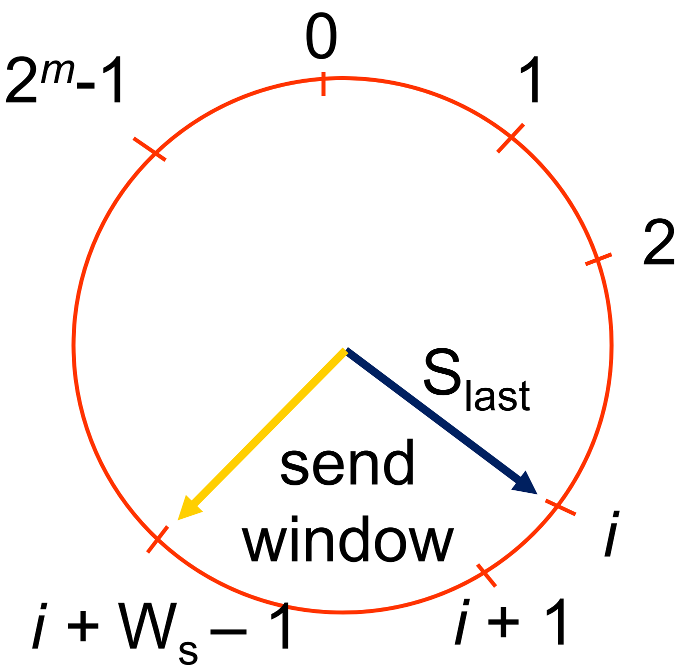
Since fr3 arrives, B knows fr2 is lost.

Transmitter and Receiver of Selective ARQ



Send & Receive Windows

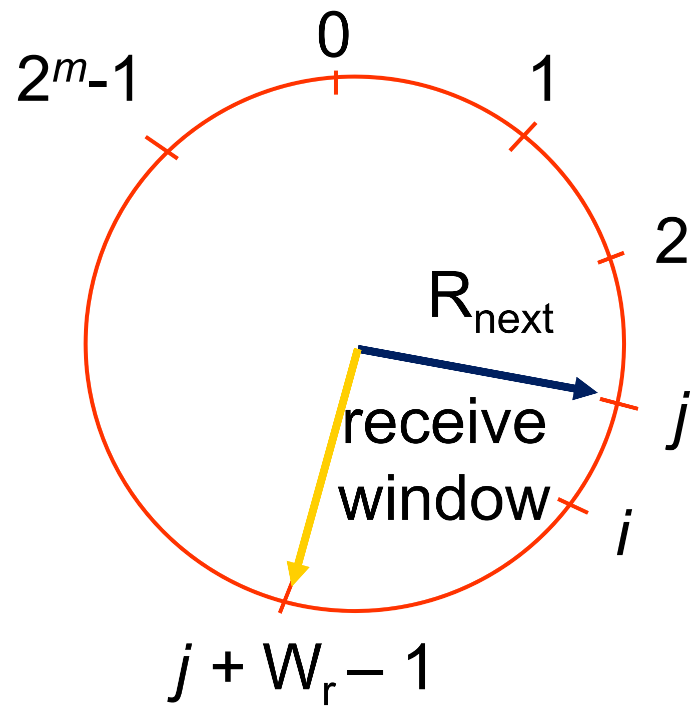
Transmitter



Moves k forward when ACK arrives with $R_{next} = S_{last} + k$

$k = 1, \ldots, W_s-1$

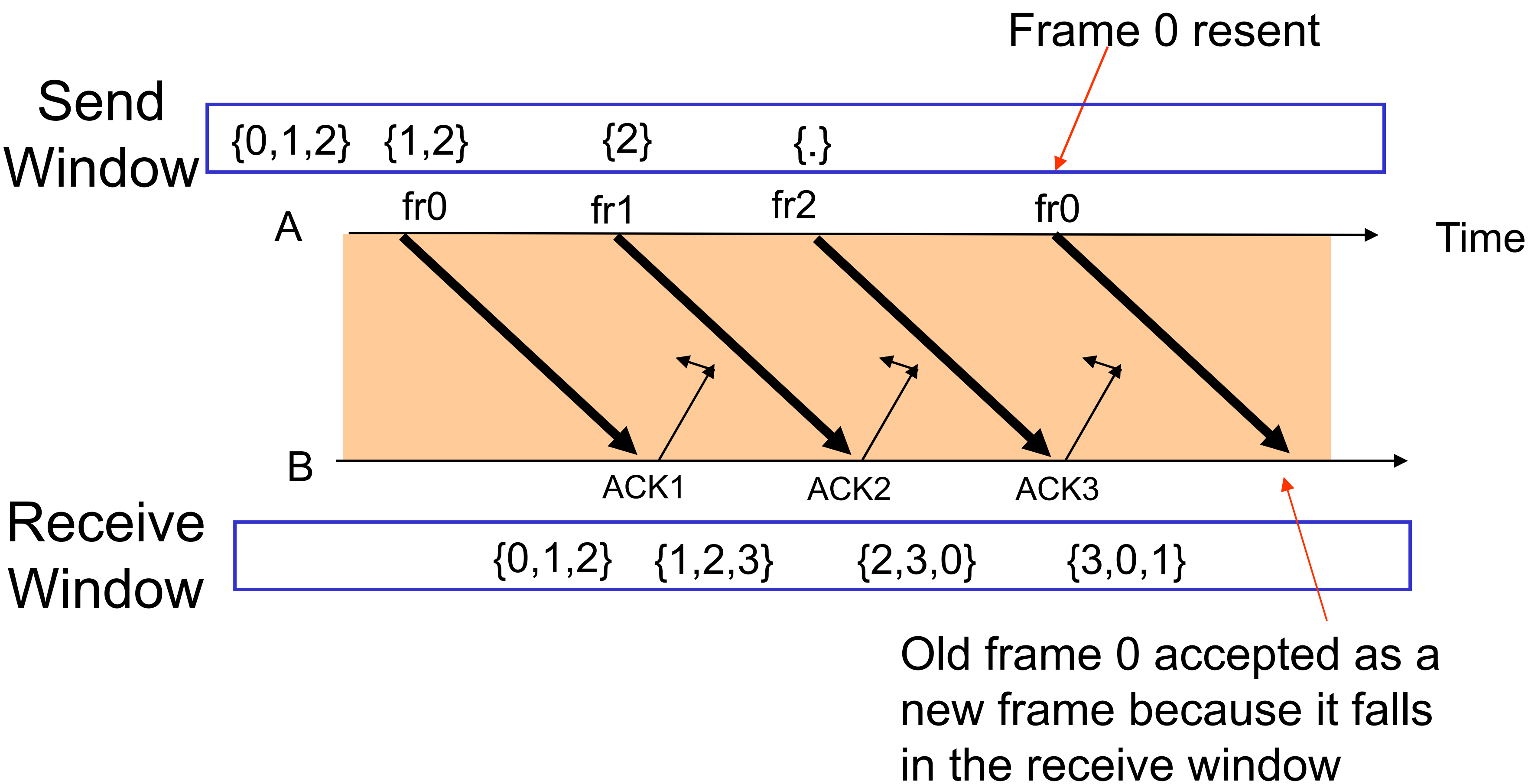
Receiver



Moves forward by 1 or more when frame arrives with Seq. # = R_{next}

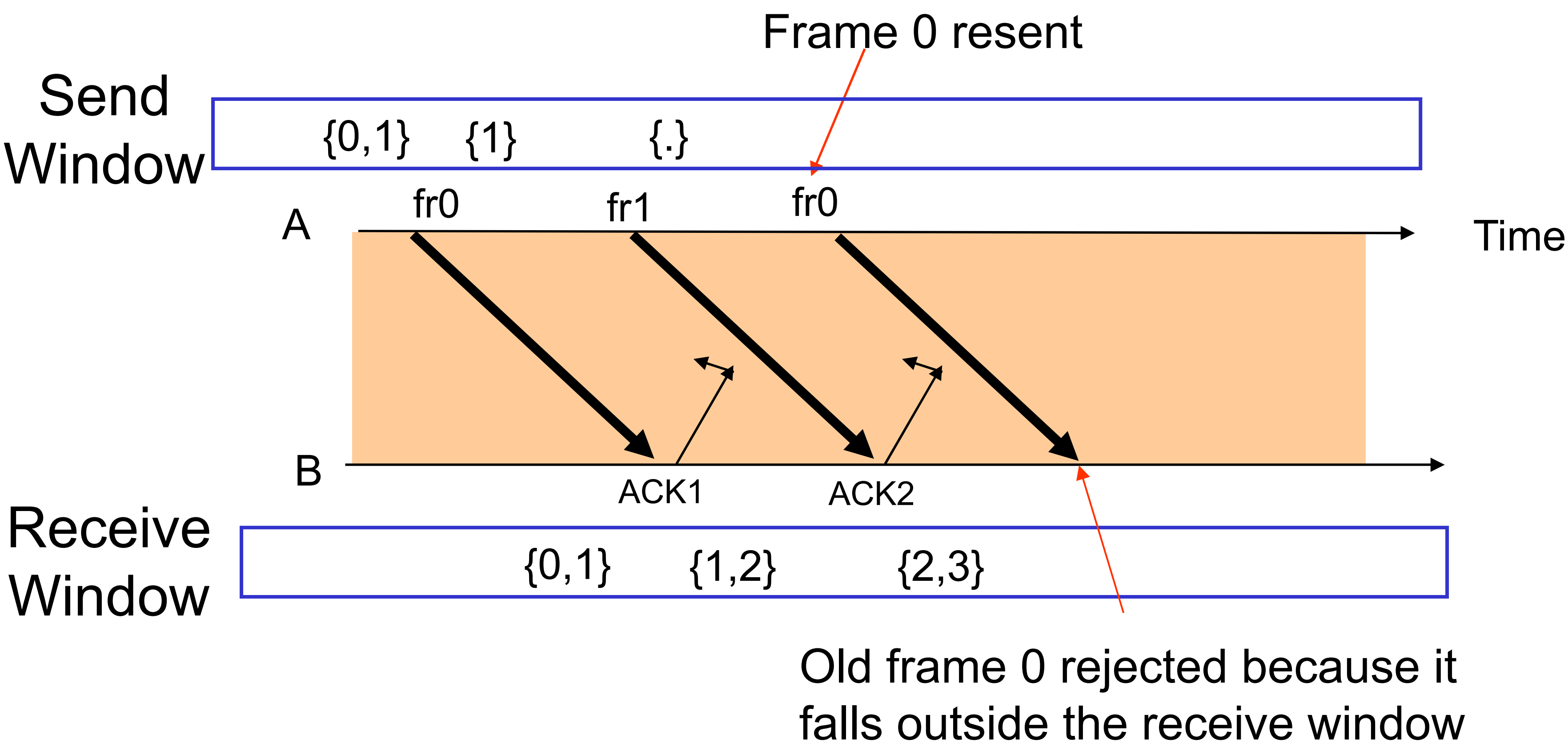
What size W_s and W_r allowed? (Example 1)

- Example: $M=2^2=4$, $W_s=3$, $W_r=3$



What size W_s and W_r allowed? (Example 2)

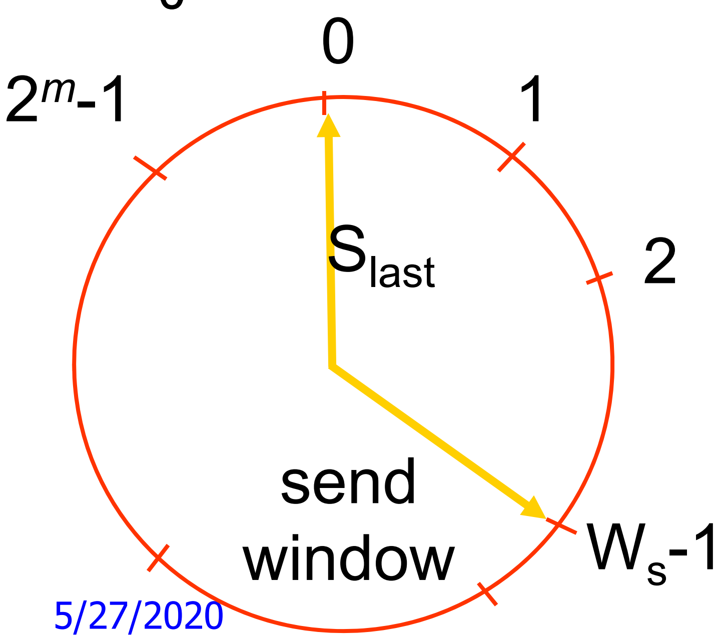
- Example: $M=2^2=4$, $W_s=2$, $W_r=2$

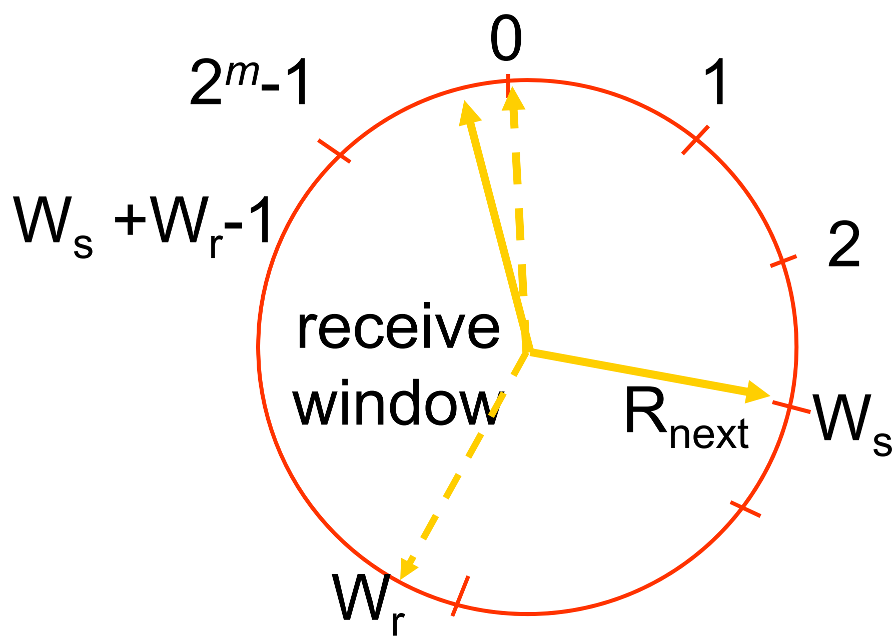


Maximum Windows

Ws+Wr<=2^m

- $W_s + W_r = 2^m$ is maximum allowed for m-bit SN
- Why?
  - Transmitter sends frames 0 to Ws-1; send window empty
  - All arrive at receiver
  - All ACKs lost
  - Transmitter resends frame 0
  - Receiver window starts at {0, …, W_r-1}
  - Window slides forward to {W_s,…,W_s+W_r-1}
  - Receiver rejects frame 0 because it is outside receive window





Applications of Selective Repeat ARQ

- *TCP* (Transmission Control Protocol): transport layer protocol uses variation of selective repeat to provide reliable stream service
- *Service Specific Connection Oriented Protocol*: error control for signaling messages in ATM networks

Efficiency of Selective Repeat

- Assume frame loss probability P_f, then number of transmissions required to deliver a frame is:
  - $t_f/(1-P_f)$

$$\eta_{SR} = \frac{\dfrac{n_f - n_o}{t_f/(1-P_f)}}{R} = \left(1 - \frac{n_o}{n_f}\right)(1-P_f)$$

Comparisons of ARQs (Example of BER Impact)

n_f=1250 bytes = 10000 bits, n_a=n_o=25 bytes = 200 bits

Compare S&W, GBN & SR efficiency for random bit errors with p=0, 10^{-6}, 10^{-5}, 10^{-4} and R= 1 Mbps & 100 ms

Efficiency	0	10^{-6}	10^{-5}	10^{-4}
S&W	8.9%	8.8%	8.0%	3.3%
GBN	98%	88.2%	45.4%	4.9%
SR	98%	97%	89%	36%

- *Selective Repeat outperforms GBN and S&W, but efficiency drops as error rate increases*
- *Not sensitive to large BDP*

Comparison of ARQ Efficiencies

Assume n_a and n_o are negligible relative to n_f, and $L = 2(t_{prop}+t_{proc})R/n_f = (W_s-1)$, then

Selective-Repeat:

$$\eta_{SR} = (1-P_f)(1-\frac{n_o}{n_f}) \approx (1-P_f)$$

Go-Back-N:

For $P_f \approx 0$, SR & GBN same

$$\eta_{GBN} = \frac{1-P_f}{1+(W_S-1)P_f} = \frac{1-P_f}{1+LP_f}$$

For $P_f \rightarrow 1$, GBN & SW same

Stop-and-Wait:

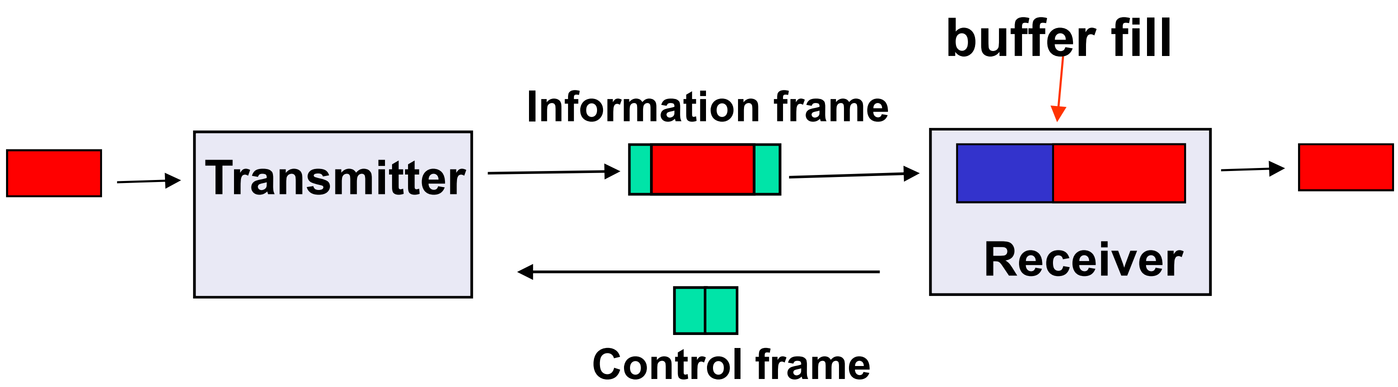
$$\eta_{SW} = \frac{(1-P_f)}{1+\frac{n_a}{n_f}+\frac{2(t_{prop}+t_{proc})R}{n_f}} \approx \frac{1-P_f}{1+L}$$

Efficiency Comparisons

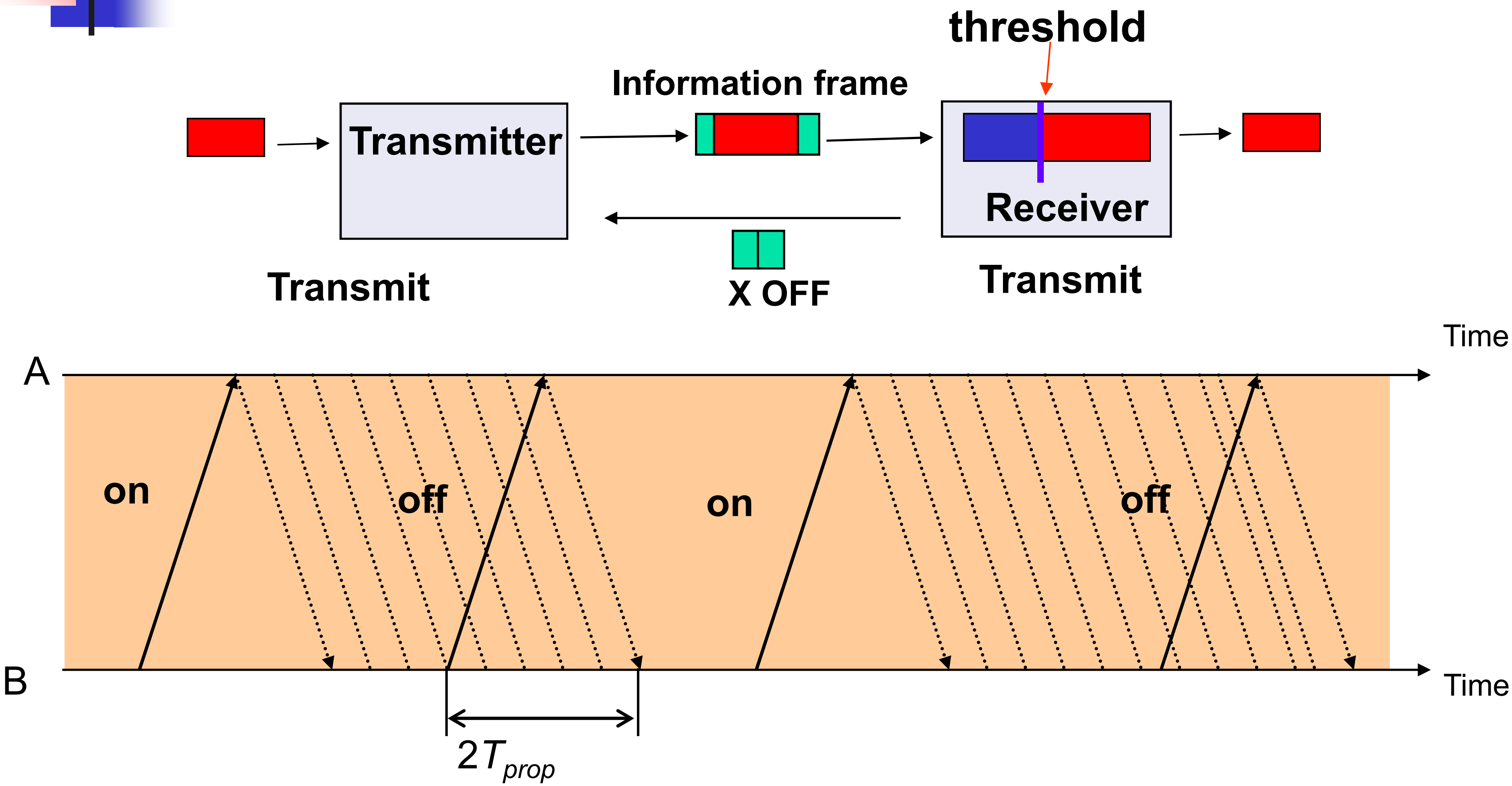
Flow Control
in the Data Link Layer

Flow Control

- Receiver has limited buffering to store arriving frames
- Several situations cause buffer overflow
  - Mismatch between sending rate & rate at which user can retrieve data
  - Surges in frame arrivals
- *Flow control* prevents buffer overflow by regulating rate at which source is allowed to send information



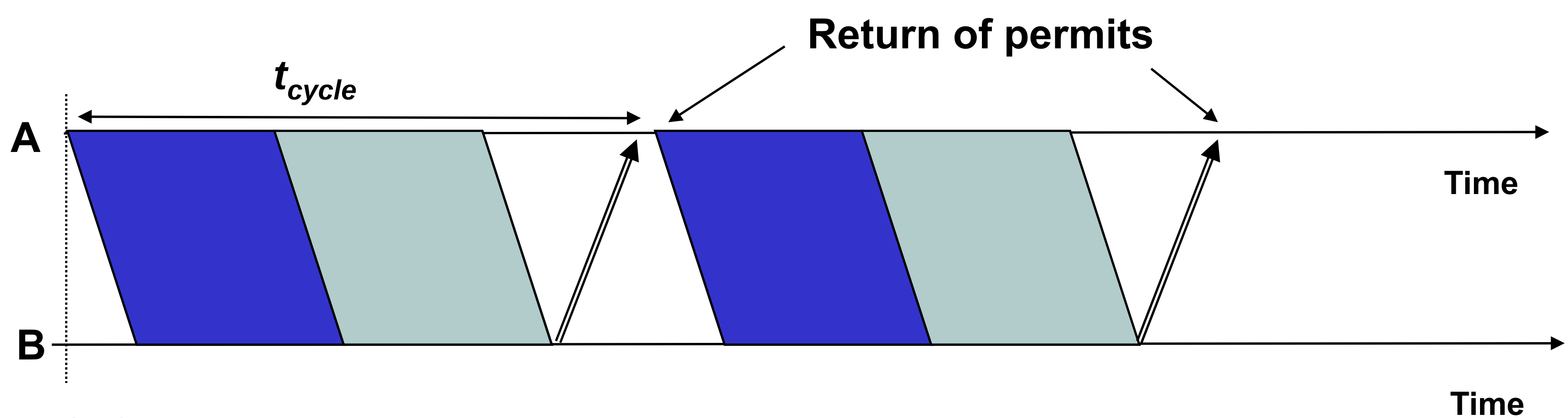
X ON / X OFF



Threshold must activate OFF signal while 2 T_{prop} R bits still remain in buffer

Window Flow Control

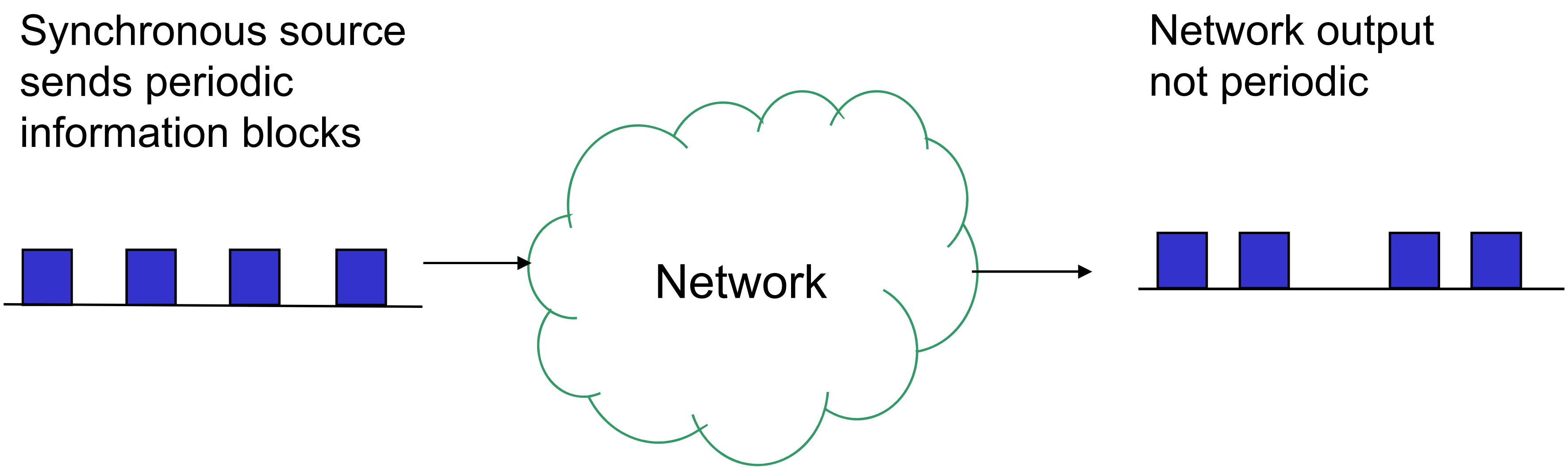
- Sliding Window ARQ method with W_s equal to buffer available
  - Transmitter can never send more than W_s frames
- ACKs that slide window forward can be viewed as permits to transmit more
- Can also pace ACKs as shown below
  - Return permits (ACKs) at end of cycle regulates transmission rate
- Problems using sliding window for both error & flow control
  - Choice of window size
  - Interplay between transmission rate & retransmissions
  - TCP separates error & flow control



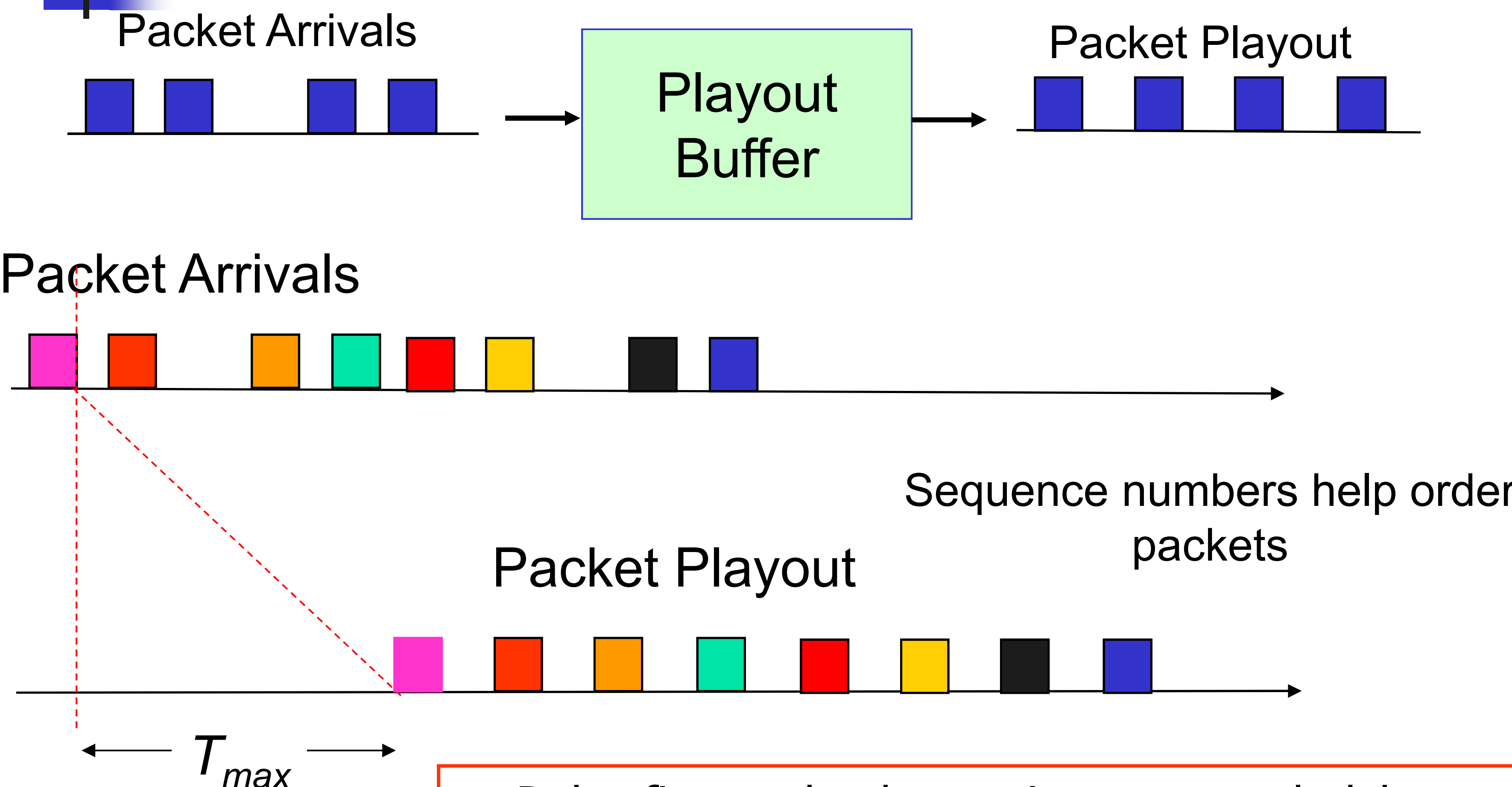
Timing Recovery

Timing Recovery for Synchronous Services

- Applications that involve voice, audio, or video can generate a synchronous information stream
- Information carried by equally-spaced fixed-length packets
- Network multiplexing & switching introduces random delays
  - Packets experience variable transfer delay
  - Jitter (variation in interpacket arrival times) also introduced
- Timing recovery re-establishes the synchronous nature of the stream



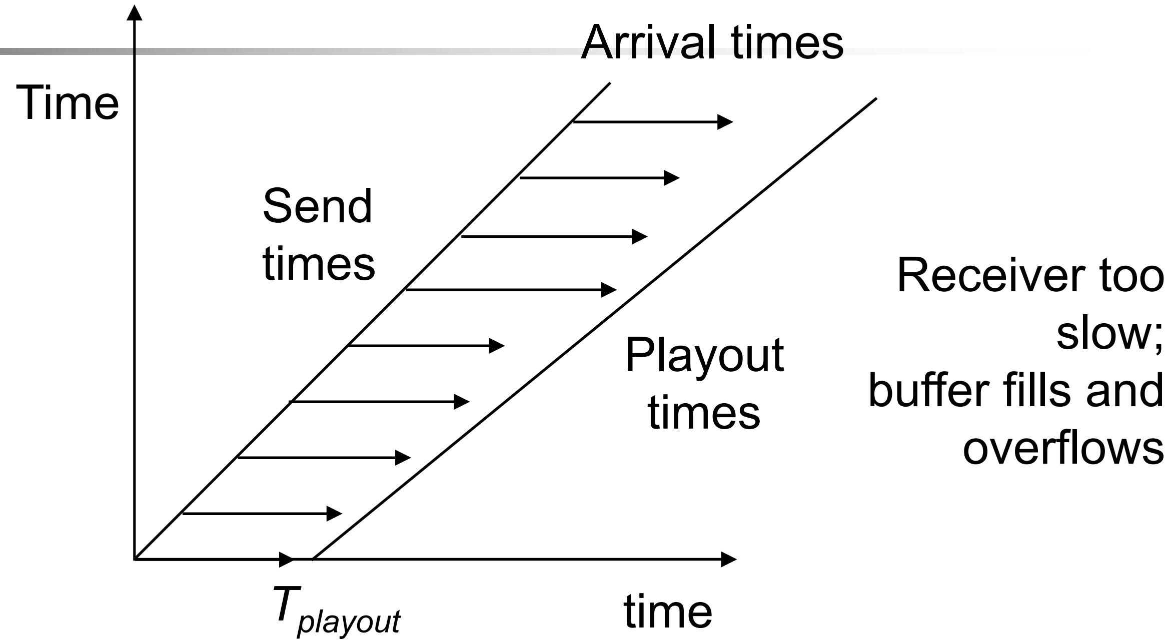
Scheme 1: Playout Buffer

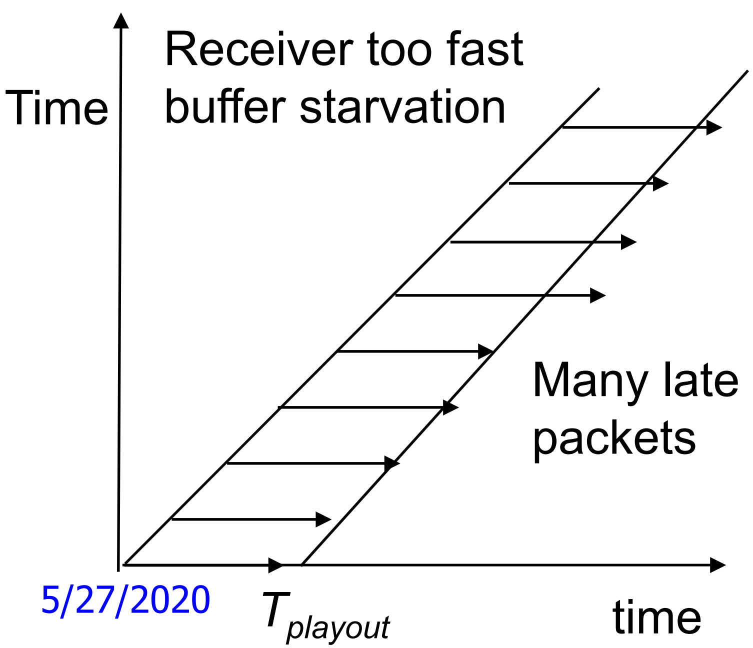


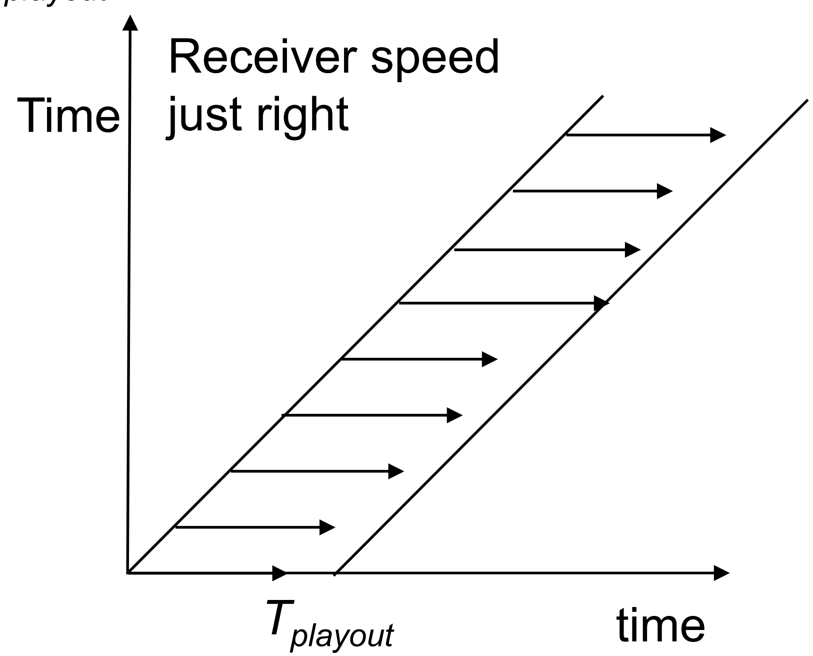
- Delay first packet by maximum network delay
- All other packets arrive with less delay
- Playout packet uniformly thereafter

Different Scenarios of Playout and Motivation for Scheme 2

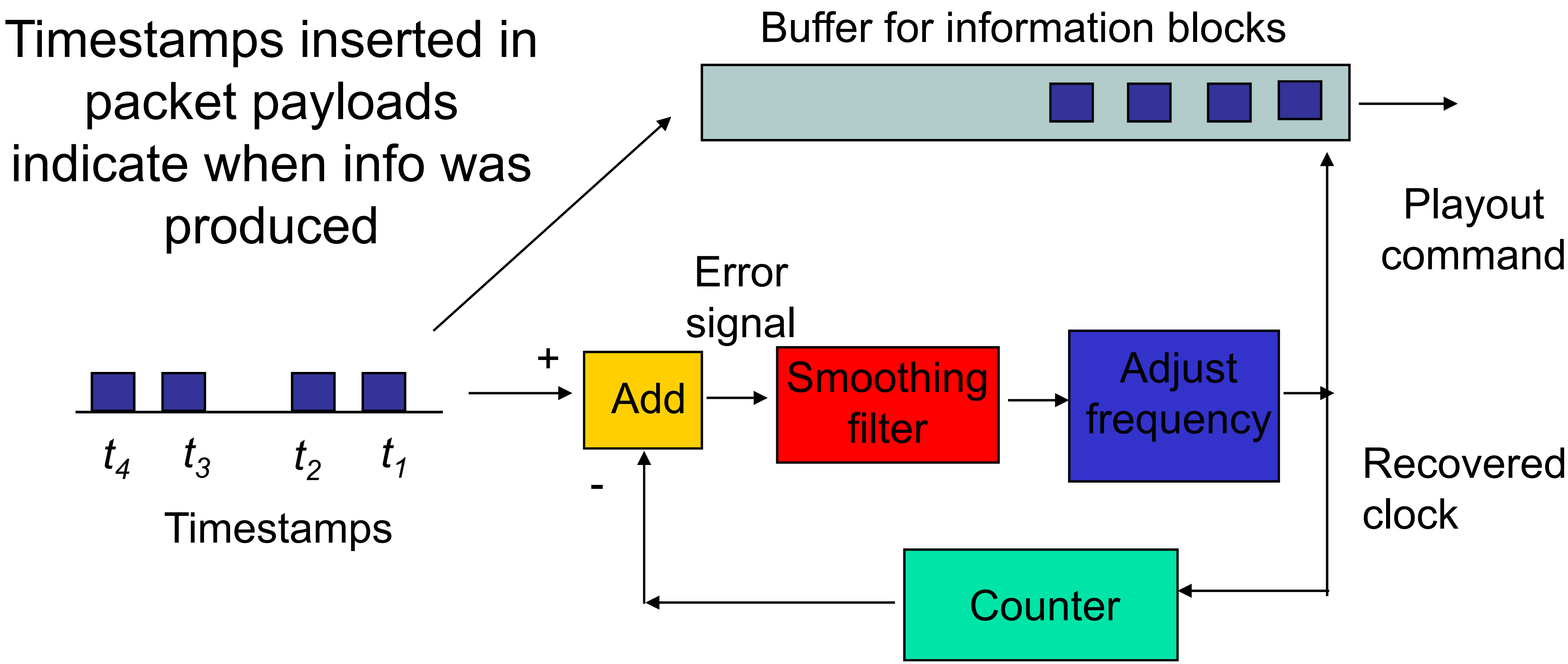
Playout clock must be synchronized to transmitter clock







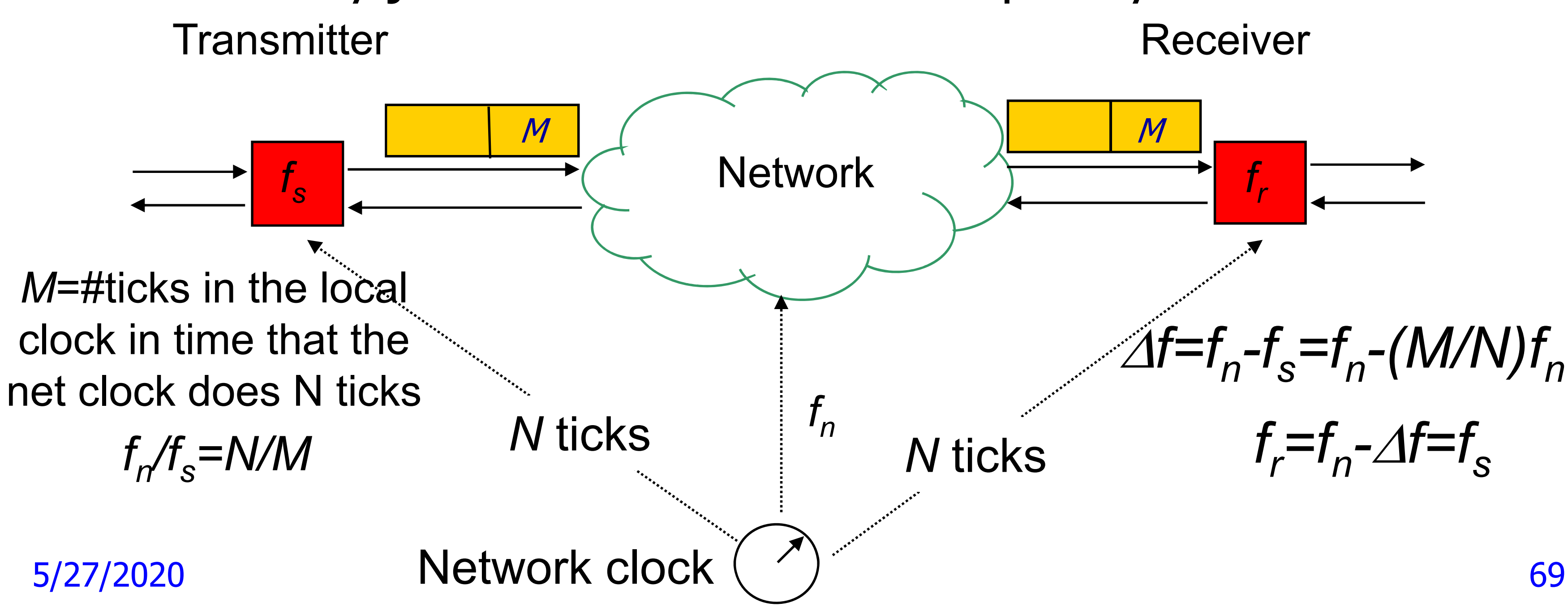
Scheme 2: Clock Recovery Based on Frequency Tracking



- Counter attempts to replicate transmitter clock
- Frequency of counter is adjusted according to arriving timestamps
- Jitter introduced by network causes fluctuations in buffer & in local clock

Scheme 3: Synchronization to a Common Clock

- Clock recovery simple if a common clock is available to transmitter & receiver
  - E.g. SONET network clock; Global Positioning System (GPS)
- Transmitter sends the value of *M* to the receiver
  - *N* is fixed, but *M* is variable according to changing time interval between packets
- Receiver derives Δf and then adjusts network frequency
- Packet delay jitter can be removed completely



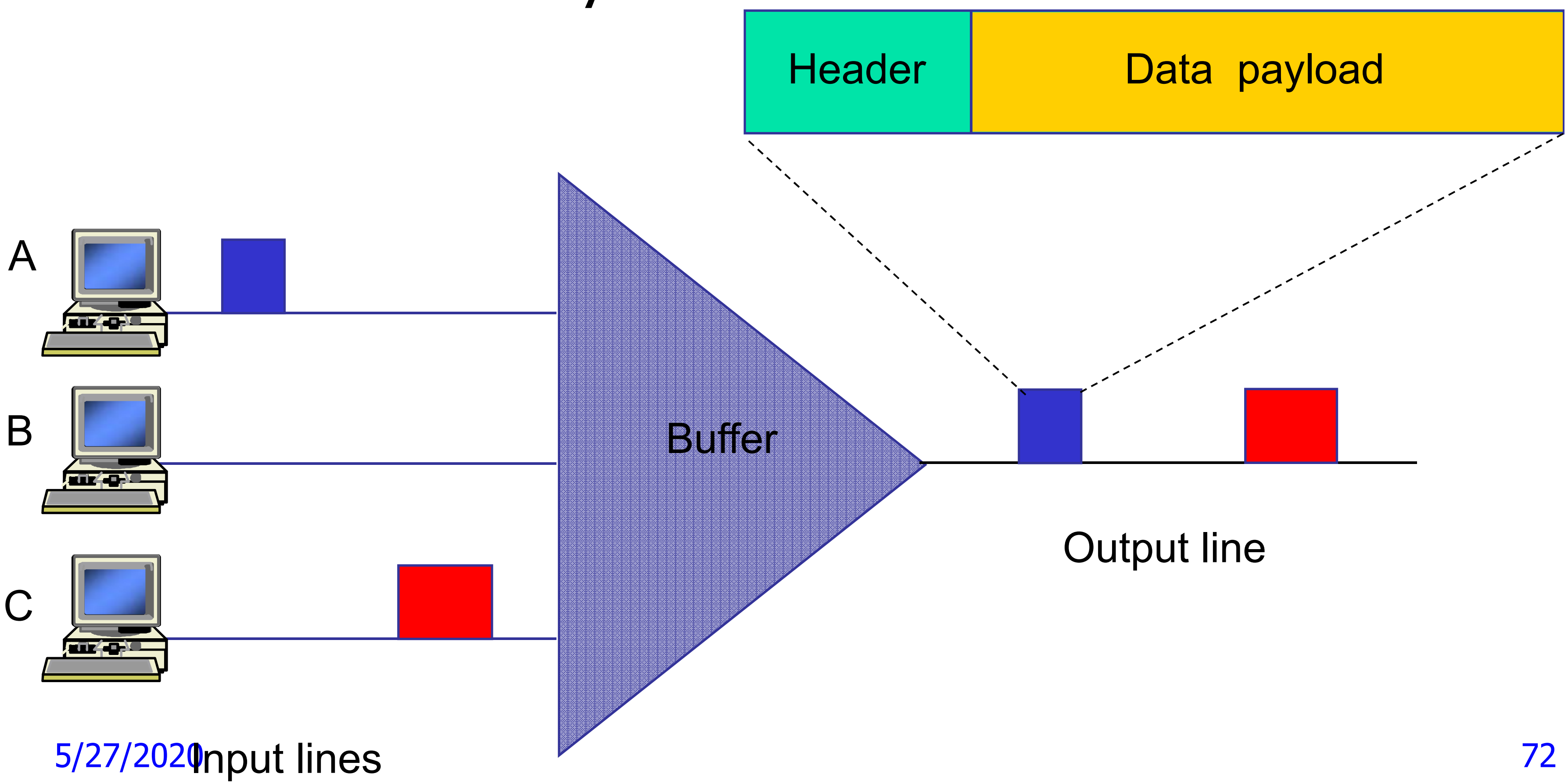
Comments on the Playout Clock Frequency at the Receiver

- The playout frequency cannot rely on number of packets in the receiving buffer
  - The variation in buffer length is impacted by network performance (more specifically delay jitter of packets)
- Scheme 1
  - Playout frequency is set according to a predetermined value, which is not adaptive to delay jitter (lead to fast or slow playout)
  - Not good for variable time intervals in original packets; not for interactive
- Scheme 2
  - Rely on timestamp in each packet to derive an adaptive playout frequency
    - E.g., if the next packet playout time is smaller than the timestamp, then decrease frequency; otherwise, increase frequency.
  - Adaptive to variable time intervals (jitter still exists), but too much overhead
- Scheme 3
  - Rely on common clock to accurately find out the playout frequency; low overhead, no jitter

Link Layer Multiplexing

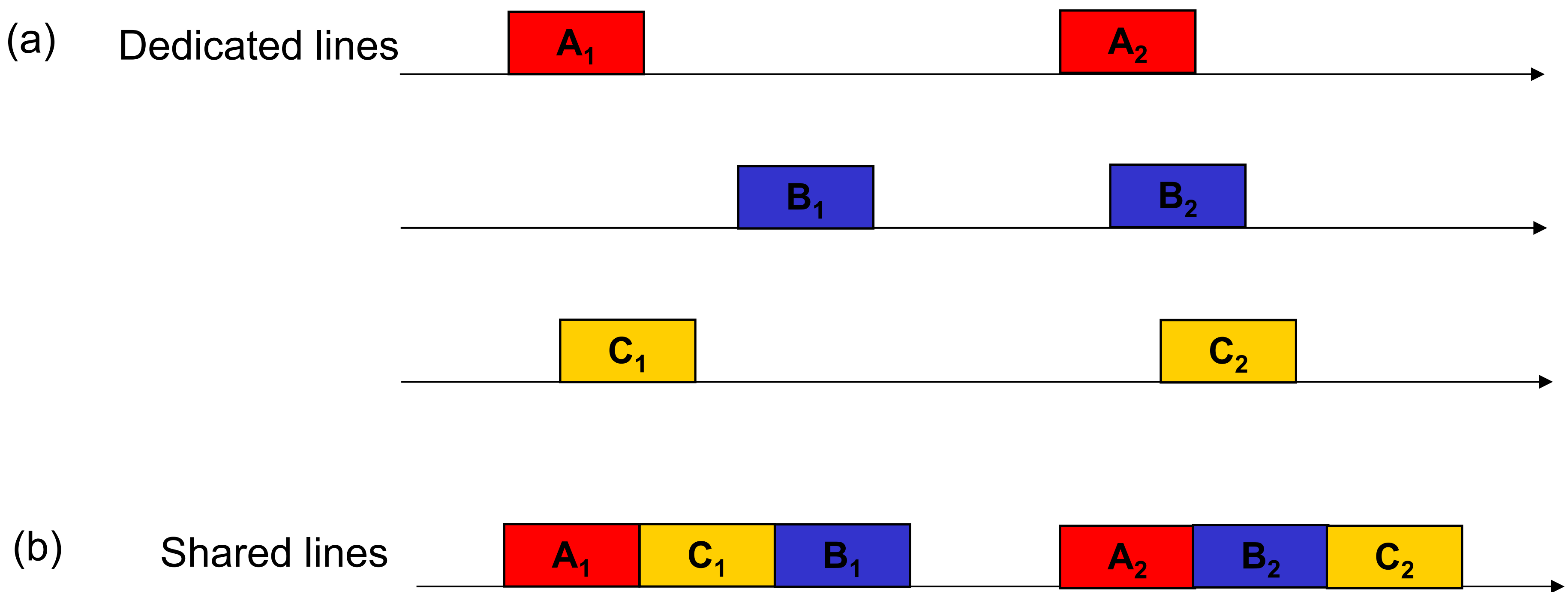
Statistical Multiplexing

- Multiplexing concentrates bursty traffic onto a shared line
- Greater efficiency and lower cost



Tradeoff Delay for Efficiency

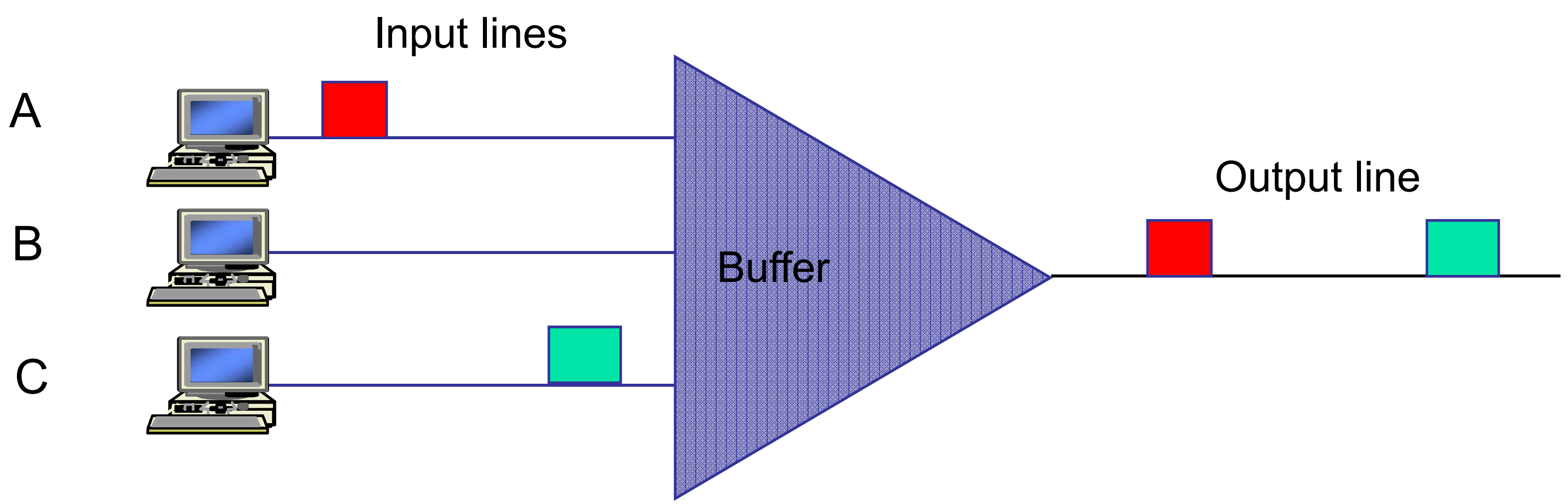
- Dedicated lines involve no waiting for other users, but lines are used inefficiently when user traffic is bursty
- Shared lines concentrate packets into shared line; packets buffered (delayed) when line is not immediately available



Multiplexer Modeling

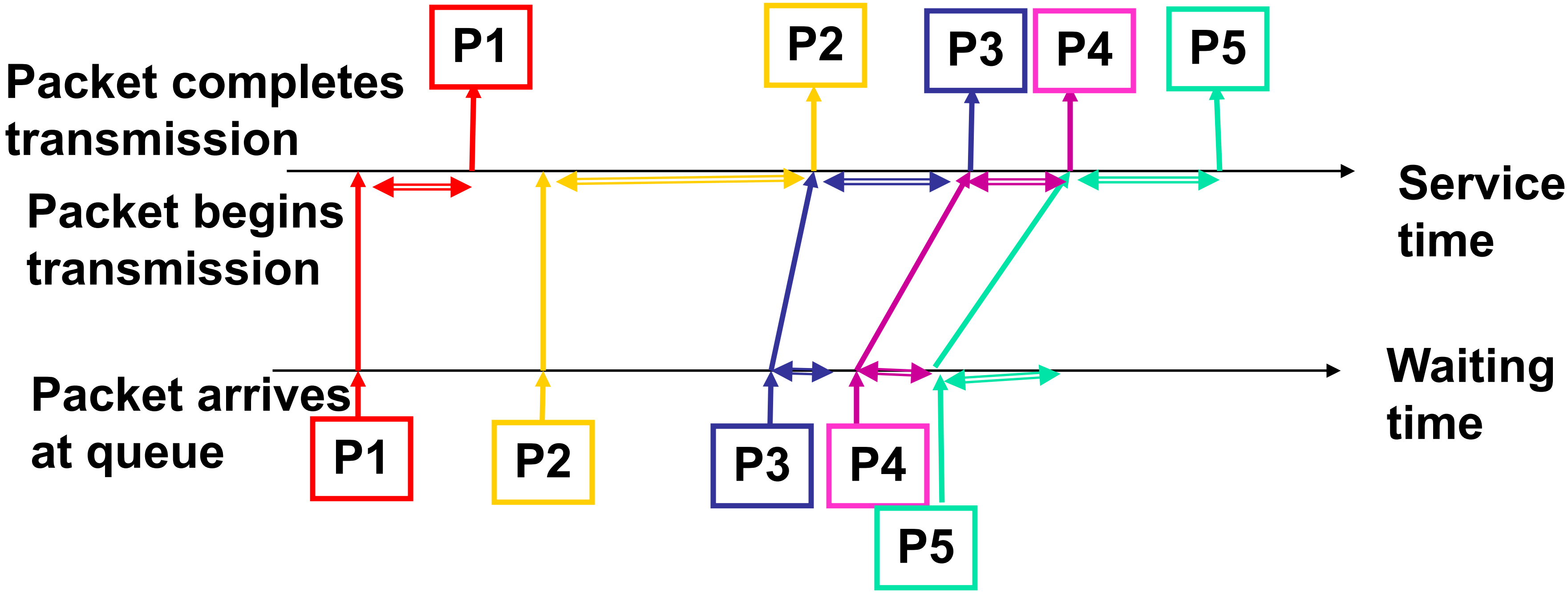
- Arrivals: What is the packet interarrival pattern?
- Service Time: How long are the packets?
- Service Discipline: What is order of transmission?
- Buffer Discipline: If buffer is full, which packet is dropped?

- Performance Measures:
- *Delay Distribution; Packet Loss Probability; Line Utilization*



Delay = Waiting + Service Times

- Packets arrive and wait for service
- Waiting Time: from arrival instant to beginning of service
- Service Time: time to transmit packet
- Delay: total time in system = waiting time + service time



Security

- *Privacy*: ensuring that information transferred cannot be read by others
- *Integrity*: ensuring that information is not altered during transfer
- *Authentication*: verifying that sender and/or receiver are who they claim to be
- *Security protocols* provide these services
- Examples: WEP, 802.11i

Link Layer Switching and Bridging

- To handle interconnections between different LANs
- *To be studied in next chapter: Chapter 4*

Examples of
The Data Link Layer Protocols

Example 1: Point-to-Point Protocol (PPP)

- Data link protocol for point-to-point lines in Internet
  - Router-router; dial-up to router
- Provides *Framing and Error Detection*
  - Character-oriented HDLC-like frame structure
    - Normally HDLC is bit-oriented.
- *Capabilities (why do we need PPP)?*
  - *One Link Control Protocol*
  - *Support Multiple Network Control Protocols simultaneously*
- *Link Control Protocol*
  - Bringing up, testing, bringing down lines; negotiating options
    - E.g., configure/set up a high speed link from multiple low-speed physical links
  - ***Authentication***: key capability in ISP access
- A family of *Network Control Protocols* specific to different network layer protocols
  - IP, OSI network layer, IPX (Novell), Appletalk

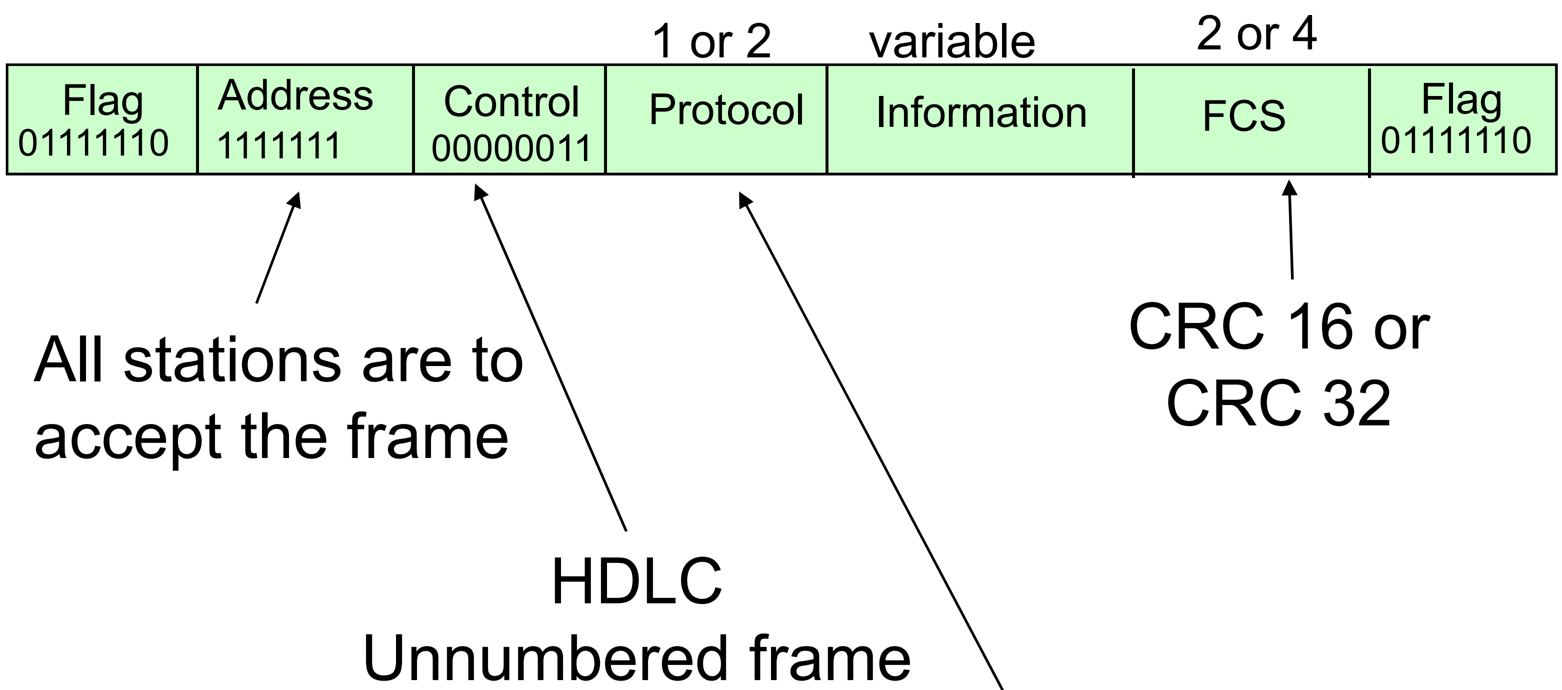
PPP Applications

PPP used in many point-to-point applications

- Telephone Modem Links 30 kbps
- Packet over SONET 600 Mbps to 10 Gbps
  - IP→PPP→SONET

- PPP is also used over shared links such as Ethernet to provide LCP, NCP, and authentication features
  - PPP over Ethernet (RFC 2516)
  - Used over DSL

PPP Frame Format

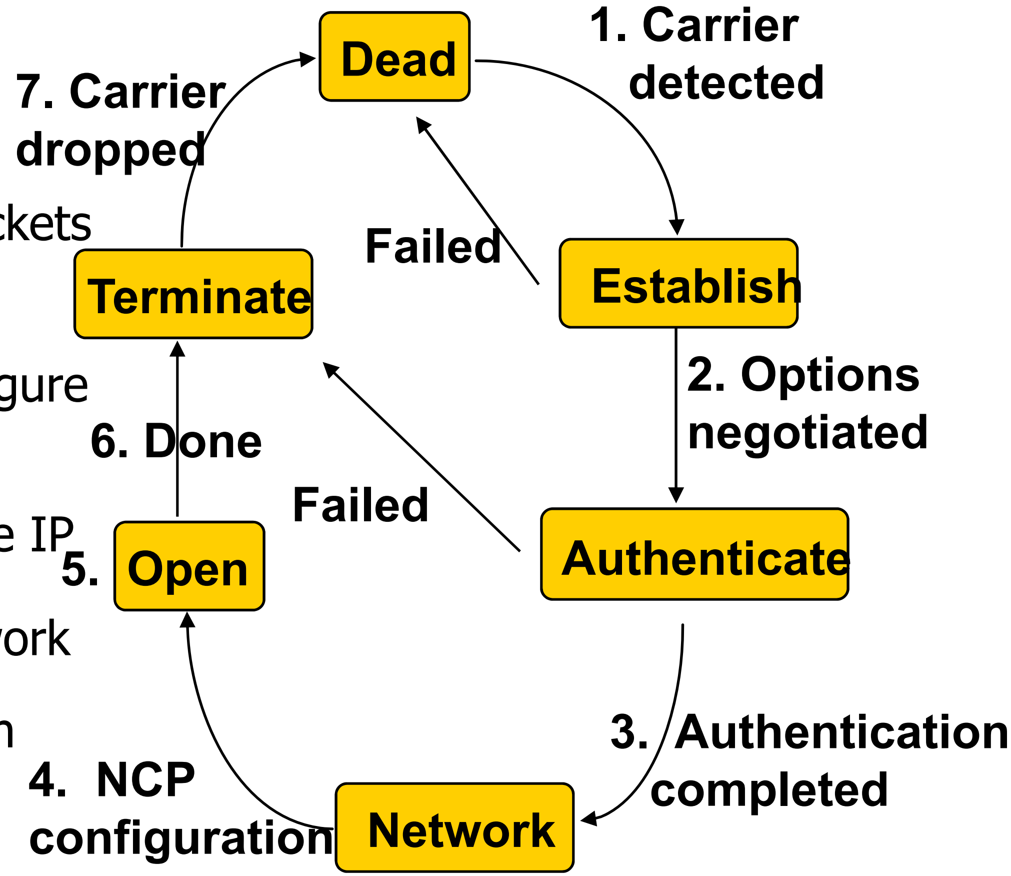


- PPP can support multiple network protocols simultaneously
- Specifies what kind of packet is contained in the payload
  - e.g. LCP, NCP, IP, OSI CLNP, IPX...

PPP Phases

Home PC to Internet Service Provider

1. PC calls router via modem
2. PC and router exchange LCP packets to negotiate PPP parameters
3. Check on identities
4. NCP packets exchanged to configure the network layer, e.g. TCP/IP (requires IP address assignment)
5. Data transport, e.g. send/receive IP packets
6. NCP used to tear down the network layer connection (free up IP address); LCP used to shut down data link layer connection
7. Modem hangs up



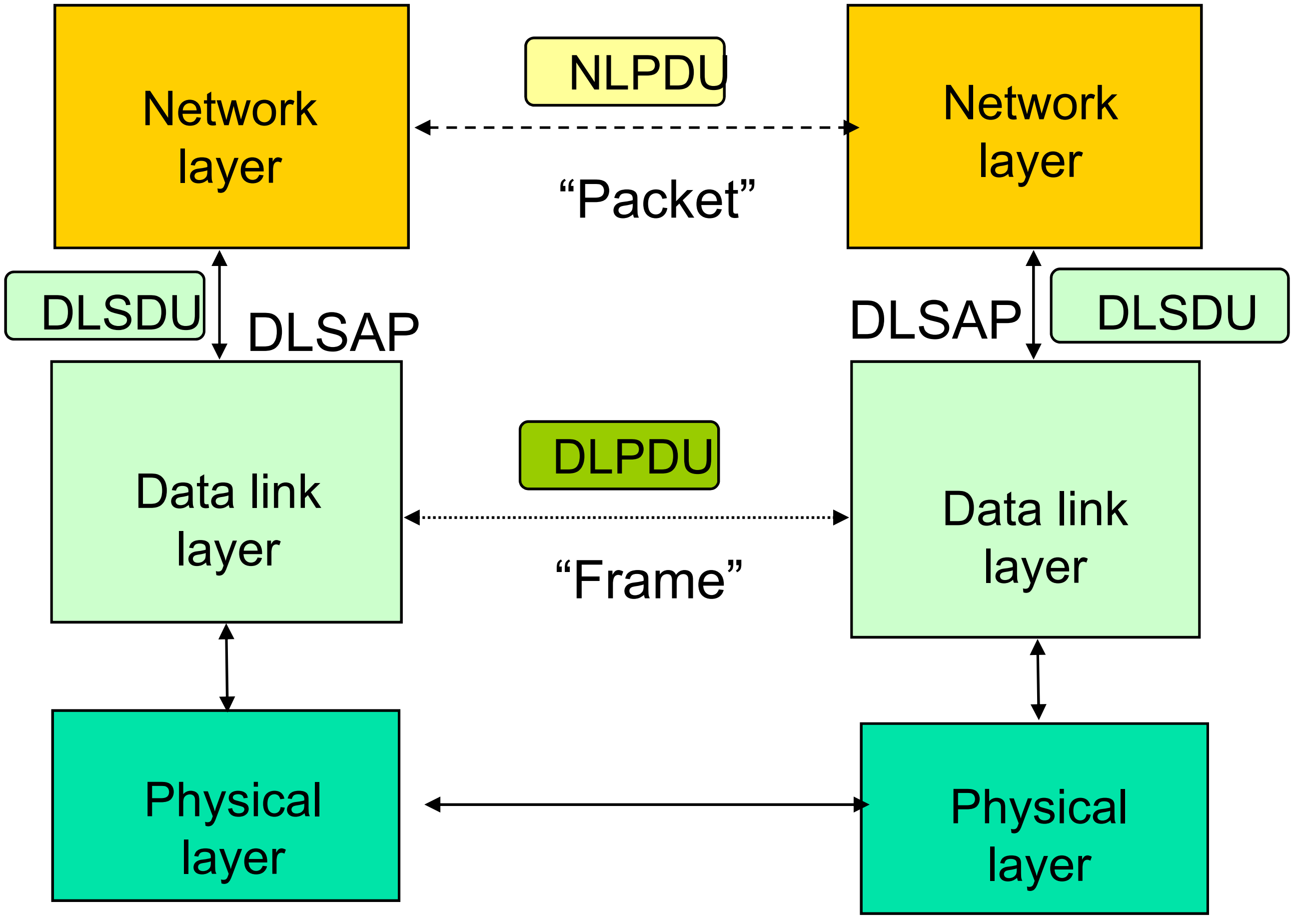
PPP Authentication

- Password Authentication Protocol
  - Initiator must send ID & password
  - Authenticator replies with authentication success/fail
  - After several attempts, LCP closes link
  - Transmitted unencrypted, susceptible to eavesdropping
- Challenge-Handshake Authentication Protocol (CHAP)
  - Initiator & authenticator share a secret key
  - Authenticator sends a challenge (random # & ID)
  - Initiator computes cryptographic checksum of random # & ID using the shared secret key
  - Authenticator also calculates cryptographic checksum & compares to response
  - Authenticator can reissue challenge during session

Example 2: High-Level Data Link Control (HDLC)

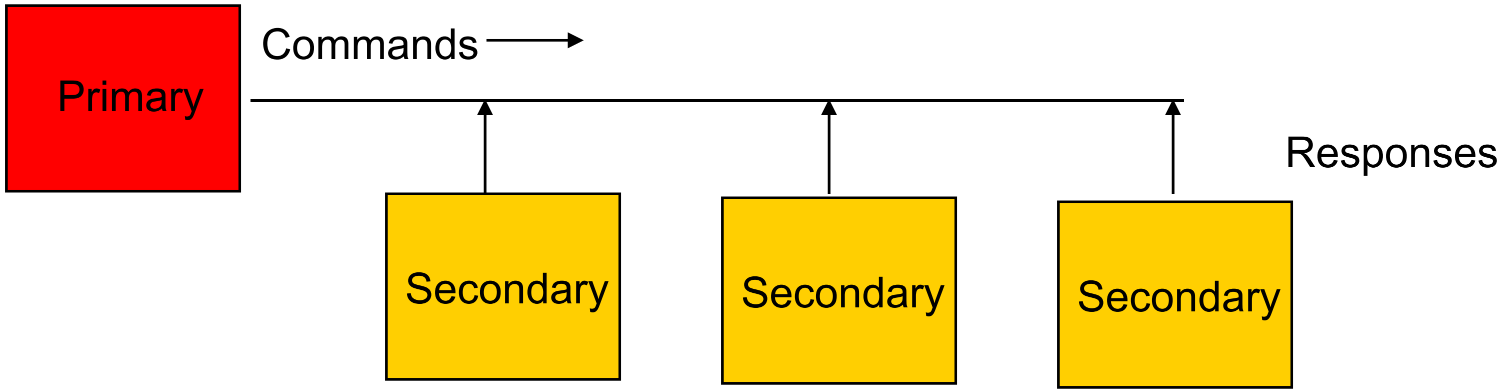
- Bit-oriented data link control
- Derived from IBM Synchronous Data Link Control (SDLC)
- Related to Link Access Procedure Balanced (LAPB)
  - LAPD in ISDN
  - LAPM in cellular telephone signaling
- Services for network layer
  - Connection-oriented
  - Connectionless, acknowledged
  - Connectionless, unacknowledged

Protocol Stack

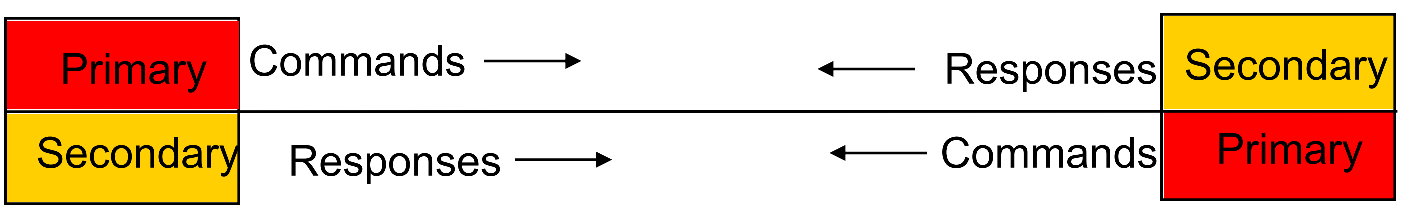


HDLC Data Transfer Modes

- Normal Response Mode (NRM)
  - Used in point-to-point link or polling multidrop lines



- Asynchronous Balanced Mode (ABM)
  - Used in full-duplex point-to-point links



- Mode is selected during connection establishment

HDLC Frame Format

- Control field gives HDLC its functionality
- Codes in fields have specific meanings
  - Flag: delineate frame boundaries
  - Address: identify *secondary* station (1 or more octets)
    - In ABM mode, a station can act as primary or secondary so address changes accordingly
  - Control: purpose & functions of frame (1 or 2 octets)
  - Information: contains user data; length not standardized, but implementations impose maximum
  - Frame Check Sequence: 16- or 32-bit CRC

Flag	Address	Control	Information	FCS	Flag

Control Field Format

Information Frame

1	2-4	5	6-8
0	N(S)	P/F	N(R)

Supervisory Frame see P91

1	0	S	S	P/F	N(R)

Unnumbered Frame

1	1	M	M	P/F	M	M	M

- **S: Supervisory Function Bits**
- **N(R): Receive Sequence Number**
- **N(S): Send Sequence Number**

- **M: Unnumbered Function Bits**
- **P/F: Poll/final bit used in interaction between primary and secondary**

Information frames

- Each I-frame contains sequence number N(S)
- Positive ACK piggybacked
  - N(R)=Sequence number of *next* frame expected acknowledges all frames up to and including N(R)-1
- 3 or 7 bit sequence numbering
  - Maximum window sizes 7 or 127 (extended case: control field =16 bits) (for Go back N ARQ)
- Poll/Final Bit
  - NRM: Primary polls station by setting P=1; Secondary sets F=1 in *last* I-frame in response
  - Primaries and secondaries always interact via *paired* P/F bits

HDLC Error Detection & Loss Recovery

- Frames lost due to loss-of-synch or receiver buffer overflow
- Frames may undergo errors in transmission
- CRCs detect errors and such frames are treated as lost
- Recovery through ACKs, timeouts & retransmission
- Sequence numbering to identify out-of-sequence & duplicate frames
- HDLC provides for options that implement several ARQ methods

Supervisory frames

Used for error (ACK, NAK) and flow control (Don't Send):

- *Receive Ready* (RR), SS=00
  - ACKs frames up to N(R)-1 when piggyback not available
- *REJECT* (REJ), SS=01
  - Negative ACK indicating N(R) is the first frame not received correctly. Transmitter must resend N(R) and later frames
    - Could be faster than timeout for go back N, but timeout is still needed
- *Receive Not Ready* (RNR), SS=10
  - ACKs frame N(R)-1 & requests that no more I-frames be sent
- *Selective REJECT* (SREJ), SS=11
  - Negative ACK for N(R) requesting that N(R) be selectively retransmitted

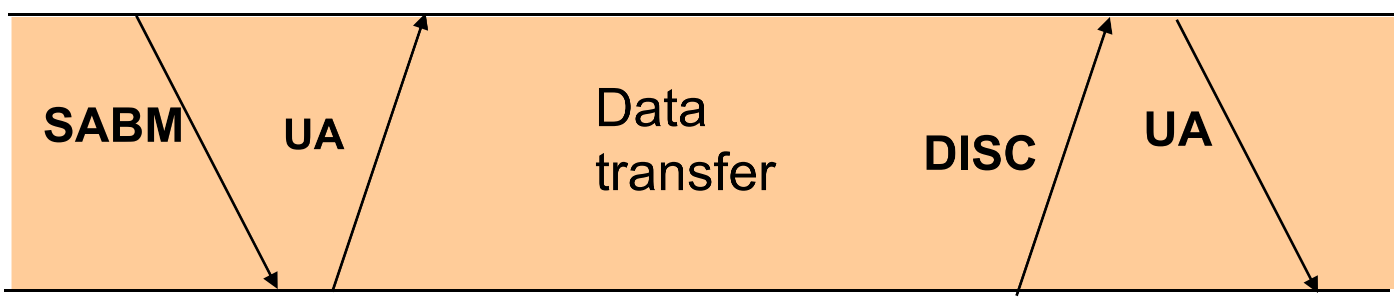
Unnumbered Frames

Multiple control functions done by unnumbered frames

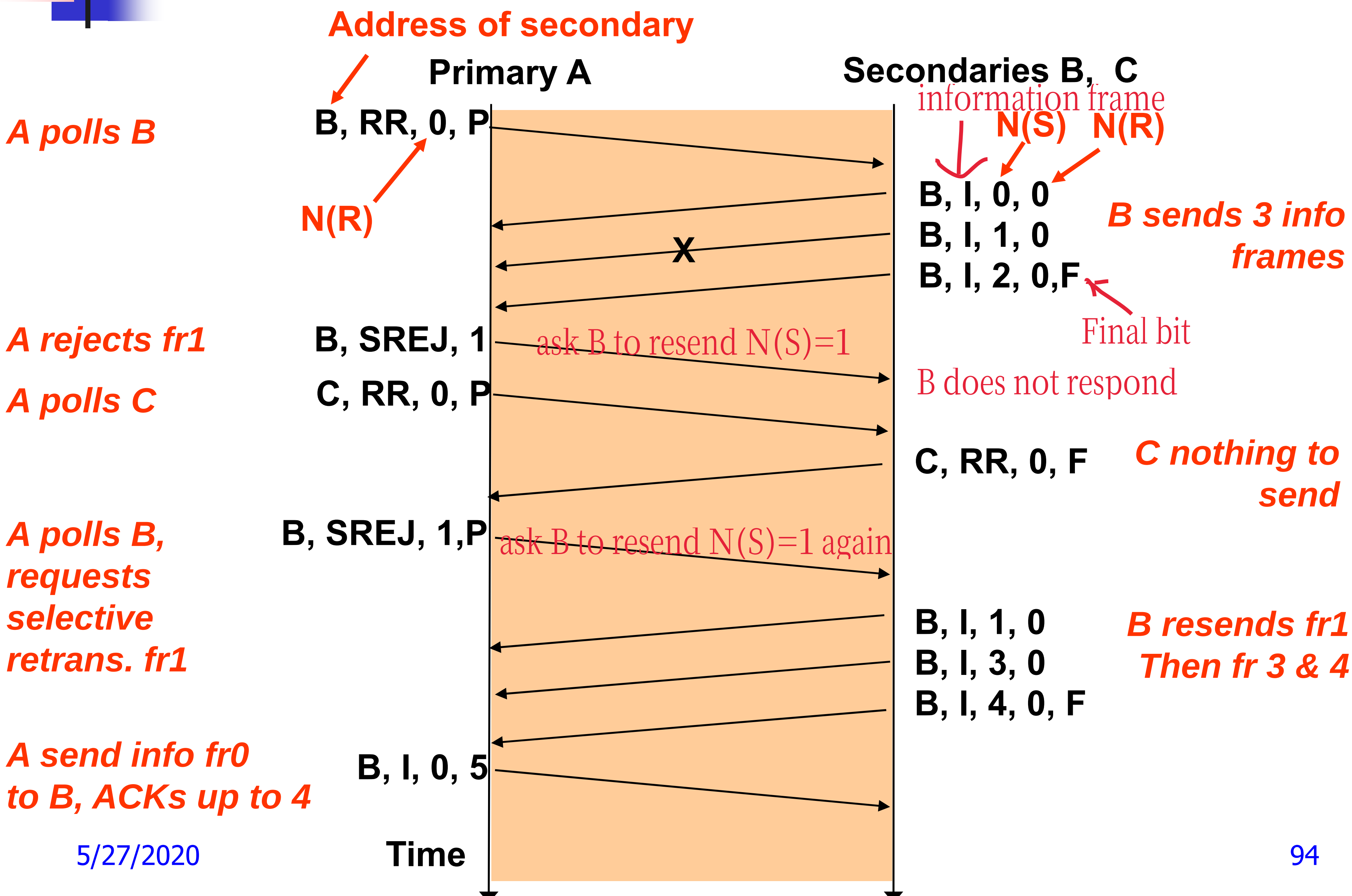
- Setting transfer modes:
  - SABM: Set Asynchronous Balanced Mode
  - UA (Unnumbered Acknowledgement): acknowledges acceptance of mode setting commands
  - DISC (Disconnect): terminates logical link connection
  - …
- Information Transfer between stations
  - UI: Unnumbered information
- Recovery used when normal error/flow control fails
  - FRMR: frame with correct FCS but impossible semantics
  - RSET: indicates sending station is resetting sequence numbers
- XID: exchange station id and characteristics

Connection Establishment & Release

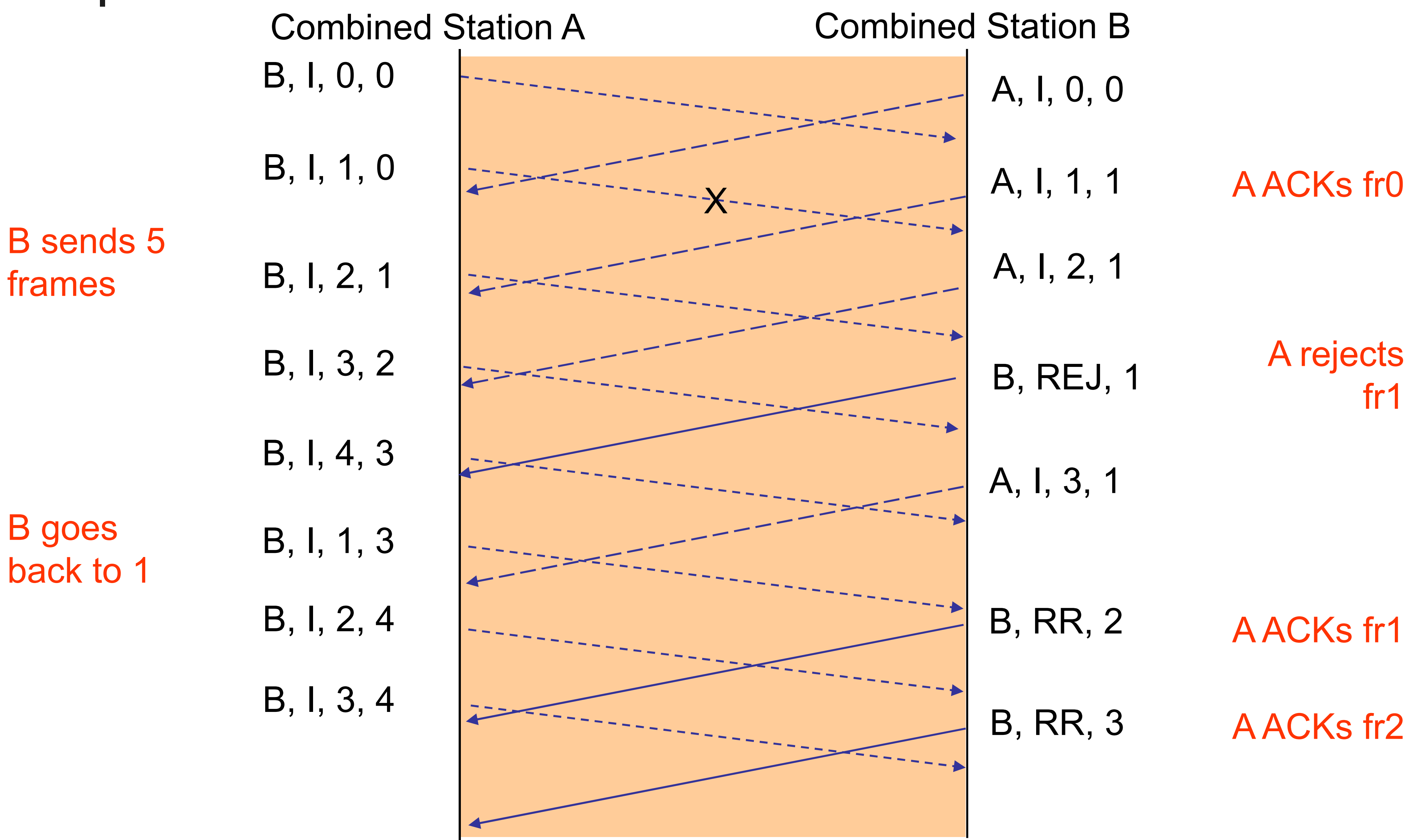
- Unnumbered frames used to establish and release data link connection
- In HDLC (example of one mode)
  - Set Asynchronous Balanced Mode (SABM)
  - Disconnect (DISC)
  - Unnumbered Acknowledgment (UA)



HDLC using NRM (polling) – Unbalanced Mode
(Mode has been set up by unnumbered frames)



Frame Exchange using ABM
(Mode has been set up by unnumbered frames)



HDLC Flow Control

- Flow control is required to prevent transmitter from overrunning receiver buffers
- Receiver can control flow by delaying acknowledgement messages
- Receiver can also use supervisory frames to explicitly control transmitter
  - Receive Not Ready (RNR) & Receive Ready (RR)