Data Link Layer, Part 2

CSC 343·643

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Flow Control

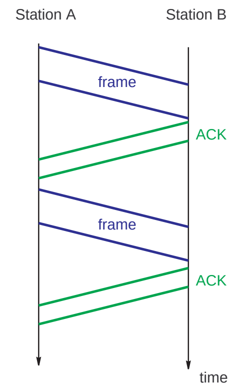
Another important issue (for the data link layer) is when the sender transmits faster than the receiver can process

- Flow control
  - Throttle the sender into transmitting no faster than the receiver can handle
  - Requires a *feedback* mechanism
- Rules typically are of the form - *Prohibit sending frames until permission given*
- There are two basic strategies for flow control
  1. Stop-and-wait
  2. Sliding window

Stop and Wait

- Rules (N.B. message broken into multiple frames)
  - Sender waits for an ACK after every frame sent
  - May send next frame after the ACK has been received
  - The data-ACK repeats until the end of the message
  - EOT sent to indicate end of message
- Acceptable for a few *large* frames

What happens if an ACK is lost?



Effect of Propagation Delay and Transmission Rate

Consider the maximum potential efficiency of a half-duplex point-to-point link using stop-and-wait

- Suppose a long message is broken into a long sequence of frames $f_1, f_2, ..., f_n$
- Using a polling procedure, the following events occur
  - Station S_1 polls station S_2
  - S_2 responds with f_1
  - S_1 sends an acknowledgement
  - S_2 sends f_2
  - S_1 sends ACK

    ⋮
  - S_2 sends f_n
  - S_1 sends ACK

- The total time to send the message is

$$T_D = T_I + n \cdot T_F$$

Where T_I is the time to initiate sequence

$$T_I = t_{prop} + t_{poll} + t_{proc}$$

and T_F = time to send one frame

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

To simplify, assume T_I is relatively small compared to the frame transmissions. Furthermore, assume the processing and ACK time is negligible. The formula is

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

- Of the time spent, only $n \cdot t_{frame}$ is used for transmitting data. Therefore the link utilization is

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

Defining $a = t_{prop}/t_{frame}$, the formula is

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

This is the utilization of the link; however, why is the actual (what the user sees) utilization even lower?

Stop and Wait Utilization Examples

- WAN example
  - Two computers 1 km apart using ATM over a fiber optic link
  - ATM *frames* (cells) are 424 bits with a bit rate of 155.52 Mbps

$$t_{frame} = \frac{424}{155.52 \times 10^6} = 2.7 \times 10^{-6} seconds$$

$$t_{prop} = \frac{10^3}{2 \times 10^8} = 0.5 \times 10^{-5} seconds$$

$$a = \frac{0.5 \times 10^{-5}}{2.7 \times 10^{-6}} = 18.5$$

$$u = \frac{1}{1 + 2 \cdot 18.5} = 0.027$$

- LAN example
  - Two computers 0.1 km apart using 10 Mbps Ethernet
  - Frame size is 1000 bits and $v = 2 \times 10^8$

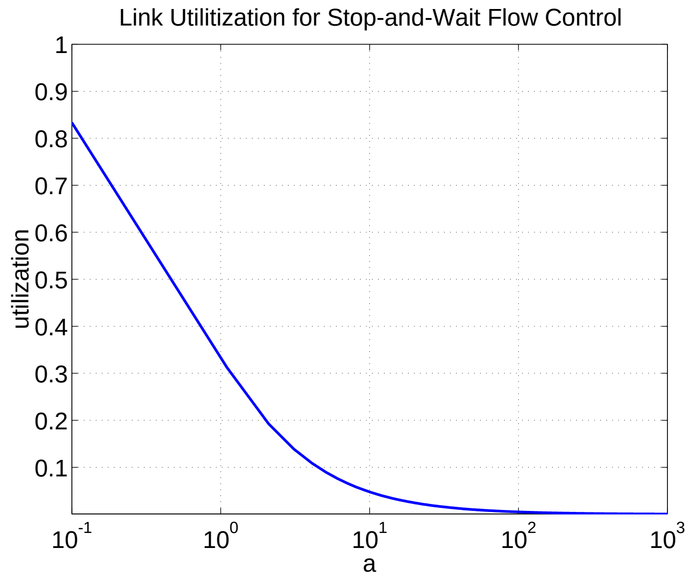
$$t_{frame} = \frac{1000}{10 \times 10^6} = 1 \times 10^{-4} seconds$$

$$t_{prop} = \frac{100}{2 \times 10^8} = 5 \times 10^{-7} seconds$$

$$a = \frac{5 \times 10^{-7}}{1 \times 10^{-4}} = 0.005$$

$$u = \frac{1}{1 + 2 \cdot 0.005} = 0.99$$

What can we conclude from the previous examples?



Sliding Window Flow Control

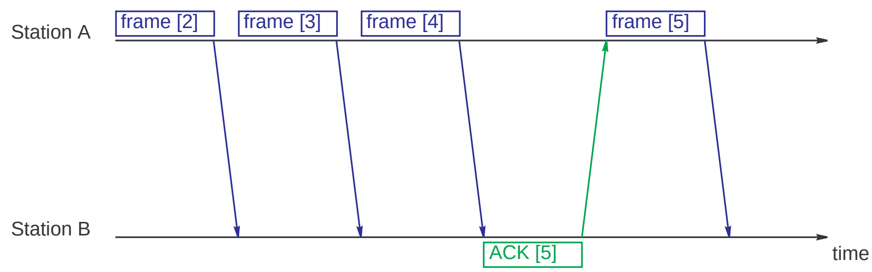
Overview

- Receiver allocates buffer space for n frames

  What is the buffer space for stop-and-wait?

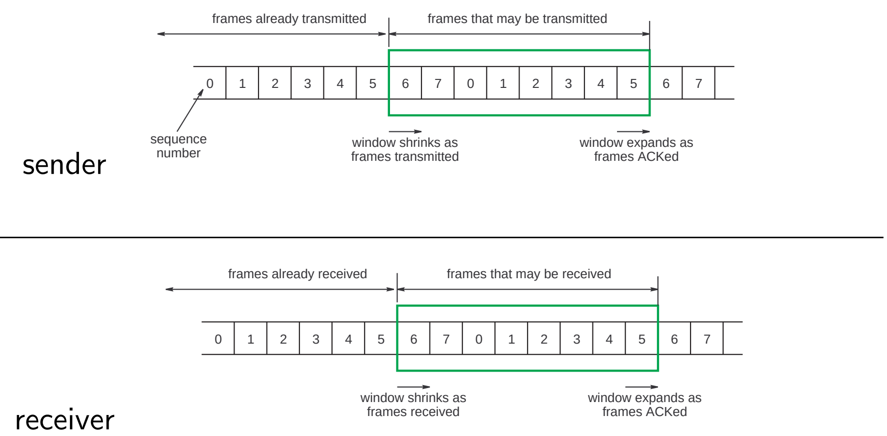
- Sender may transmit n frames without an ACK
- To keep track of which frames have be ACKed, each has a *sequence* number
- Receiver ACK's a frame by sending an ACK that includes the sequence number of the **next expected frame**
- Sender can send the next n frames **staring with** the last received sequence number

- A single ACK can acknowledge multiple frames
  - Receiver gets frames 2 and 3, but waits for frame 4 to ACK
  - Once frame 4 arrives, ACK[5] is sent to the receiver
  - Therefore frames 2, 3, and 4 are ACKed

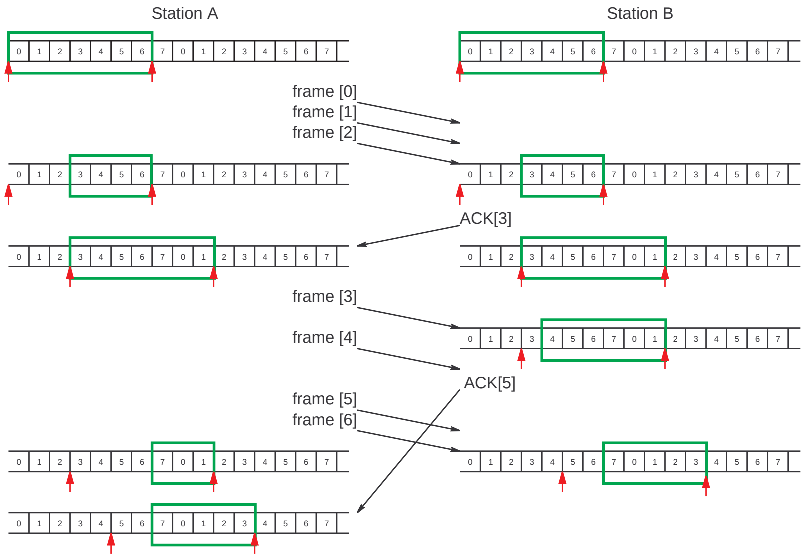


- Therefore, the sender can send multiple back-to-back frames, making better use of the channel

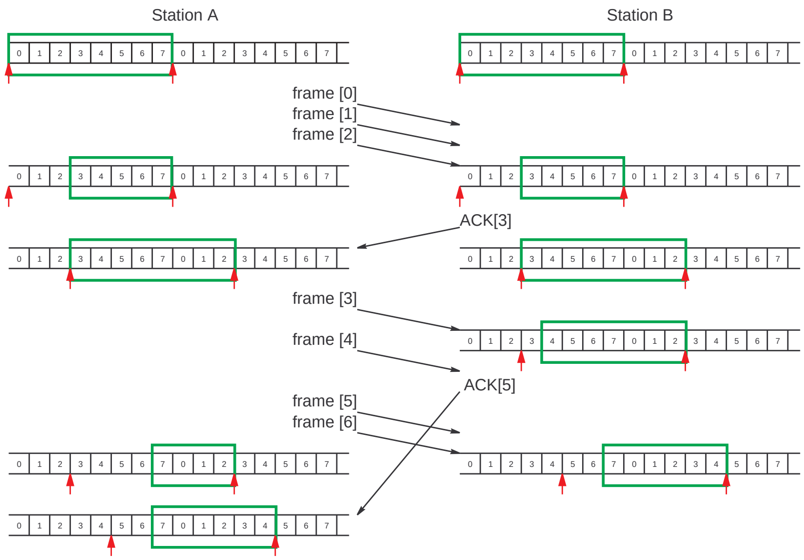
- Sequence number is a field in the frame $\Rightarrow$ finite size
- If k bits are reserved for the sequence number, then the values range from 0 to $2^k - 1$ (modulo counter)
- This can be depicted as a *sliding window*



- In the figures above, the window is represented using ______ bits



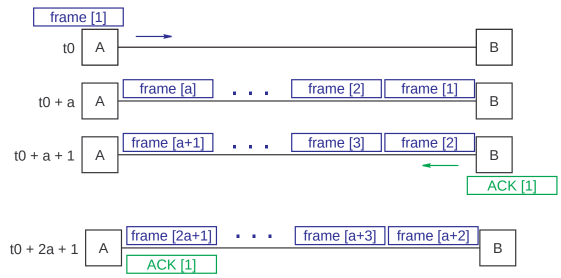
- N.B. can only send/receive n (window size) beyond last ACK[$\cdot$]
- In this example $n =$ ______ and $k =$ ______



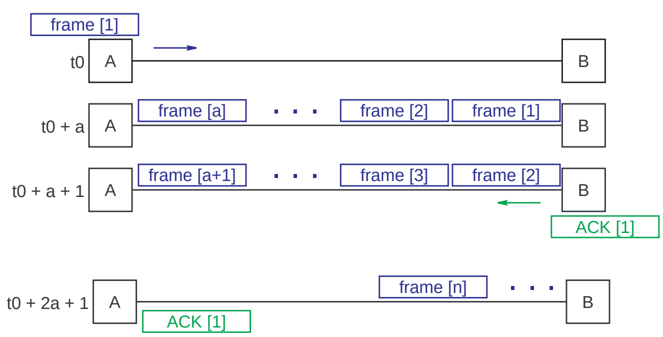
- In this example $n =$ ______ and $k =$ ______

Sliding Window Performance

- Assume a full-duplex point-to-point link using sliding window
- Efficiency depends on n (window size) and a ($\frac{t_{prop}}{t_{trans}}$)
- To simplify the analysis, normalize the frame transmission time; therefore, the propagation time is a
- There are two cases to consider
  1. ACK for the first frame reaches station A before the window is exhausted (*station A transmits without pausing*, $n > 2a + 1$)

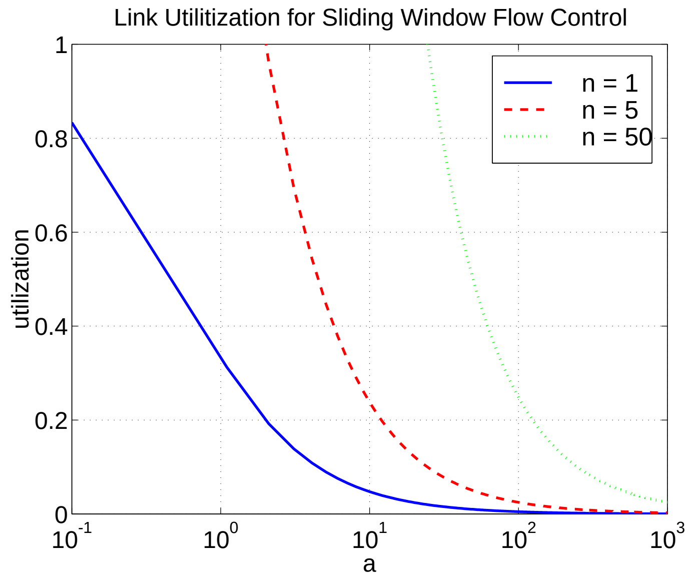


  2. Station A exhausts window before an ACK is received (*station A must pause*, $n < 2a + 1$)



- Using the two cases, the link utilization is

$$u = \begin{cases} 1 & n > 2a + 1 \\ \frac{n}{2a+1} & n < 2a + 1 \end{cases} \qquad (1)$$



Error Control

Mechanisms that detect (covered in previous slides) and correct (via retransmission) errors that may occur

- Two types of errors possible
  1. Lost frame - Frame (data or control) fails to arrive
  2. Damages frame - Frame recognized, but some bits have been changed

  What is the difference with error detection using parity?

- Error control mechanisms are referred to as **ARQ** (Automatic Repeat reQuest), there are three common versions
  1. Stop-and-wait ARQ
  2. Go-back-N ARQ
  3. Selective-reject ARQ

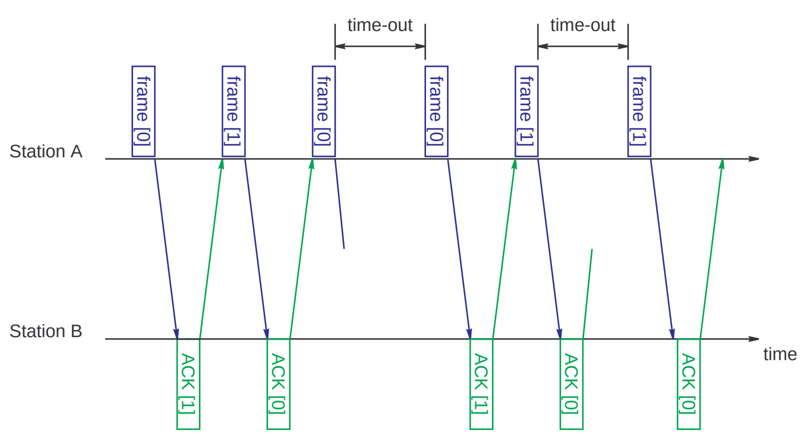
Stop-and-Wait ARQ

As previously described, sender transmits a frame then waits for ACK.

- Two types of errors may occur
  - Frame received in error (detected)
    - Receiver sends NACK to sender
    - Sender then retransmits frame
  - Frame (data) lost during transmission
    - Receiver neither ACKs nor NACKs
    - Sender *times-out* and retransmits

      What additional resources are required by the sender?
  - If the ACK is lost...
    - Frame received correctly, but ACK is lost
    - Sender times-out and retransmits
    - Receiver gets frame, it needs to identify that it is a copy

  - Avoiding the lost ACK problem
    - Label frames as 0 or 1 (alternating)
    - ACK[0] acknowledges frame[1], while ACK[1] acknowledges frame[0]



Stop-and-Wait ARQ Performance

- We have previously shown that error-free stop-and-wait achieves a maximum link utility of

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

However, now we wish to account for the possibility of errors

- Utilization can be defined as

$$u = \frac{t_{frame}}{t_{total}}$$

where t_{frame} is the time to transmit a frame, and t_{total} is the total time the line is used to transmit the frame

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

$$u = \frac{t_{frame}}{t_{frame} + 2t_{prop}}$$

We will divide by t_{frame} and use $a = \frac{t_{prop}}{t_{frame}}$

- If errors occur then

$$u = \frac{t_{frame}}{n_r \cdot t_{total}}$$

where n_r is the number of transmissions required; therefore stop-and-wait ARQ utilization is

$$u = \frac{t_{frame}}{n_r \cdot (t_{frame} + 2t_{prop})}$$

Which can be rewritten as

$$u = \frac{1}{n_r \cdot (1 + 2a)}$$

- Must determine a value for n_r based on the probability that a frame is in error p
  - Assume ACKs and NACKs are never in error
  - The probability that it will take k attempts to transmit a frame successfully is

$$p^{k-1}(1-p)$$

    which is one success after $k-1$ failures

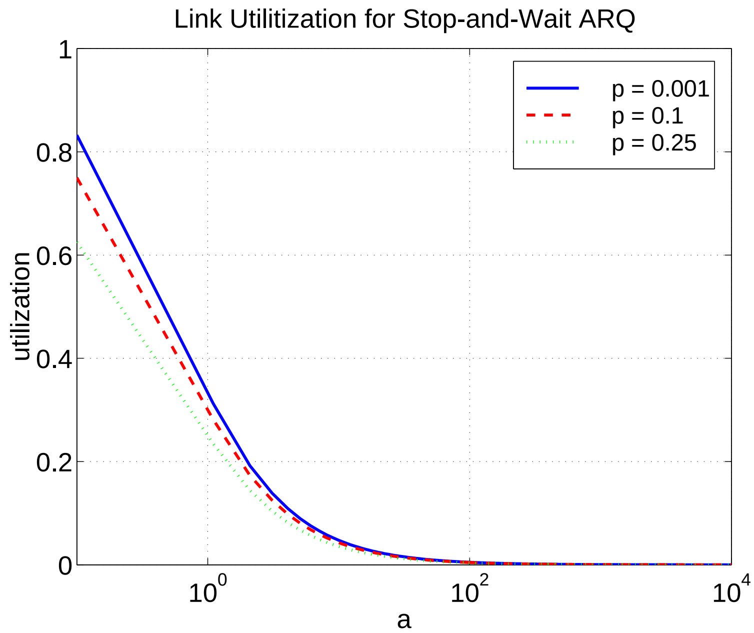
  - The expected number of transmissions is

$$n_r = E[\text{transmissions}] = \sum_{i=1}^{\infty} i \cdot p[i \text{ transmissions}]$$

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

- Therefore, the link utilization for stop-and-wait ARQ is

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



Go-Back-N ARQ

A type of *continuous ARQ*

- Similar sliding window flow control, sender may transmit multiple frames based on window size
- ACK[i] still indicates expected frame
  - Every frame need not be explicitly ACKed

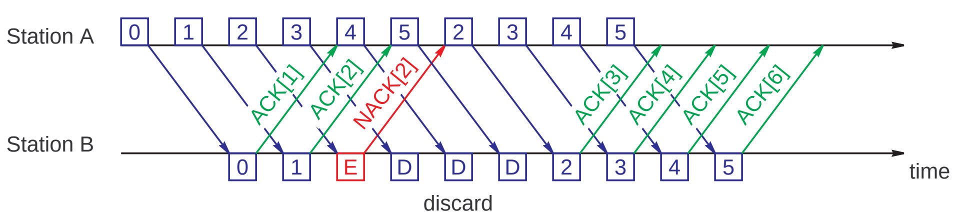
  Does sliding window flow control require each frame be explicitly ACKed?

- Modifications
  - Sender sets an *acknowledgement timer* for each frame
  - NACK[i] indicates
    * Frame i not received, resend along with any subsequent frames
    * Previous frames accepted
  - Receiver discards any frame out of order
  - Every lost/damaged frame must be NACKed
  - Maximum window size is $2^k - 1$
- There are two error cases
  1. Error/lost frame
  2. Error/lost ACK/NACK

Go-Back-N Error Cases

Frame Error

- Sender transmits FRAME[i]
- Receiver gets FRAME[i] then detects error
- Receiver transmits NACK[i], indicating FRAME[i] rejected
- Sender receives NACK[i] and must retransmit FRAME[i] and any subsequent transmitted frames



Lost frame

- FRAME[i] lost in transit (sender does not know)
- Sender sends FRAME[$i+1$]
- Receiver gets FRAME[$i+1$], which is *out-of-order*
- Receiver sends NACK[i] (first missing frame)
- Sender receives NACK[i] and must retransmit FRAME[i] and any subsequent transmitted frames

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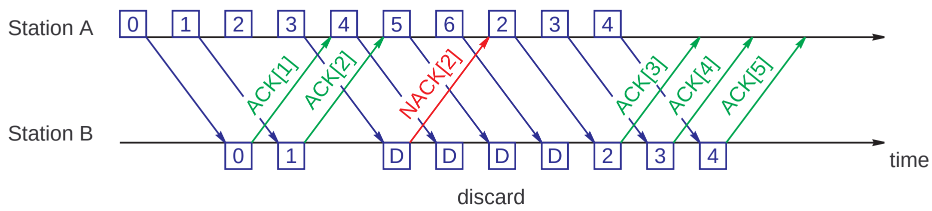
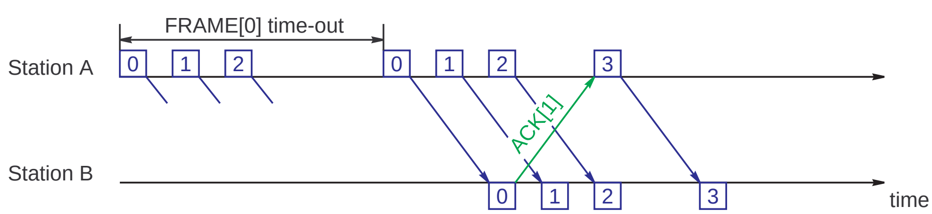


Sender Time-Out

- Sender transmits FRAME[i]

- FRAME[i] lost in transit
- Sender times-out (for ACK[i])
- Sender retransmits FRAME[i] and any subsequent frames



Damaged or Lost ACK

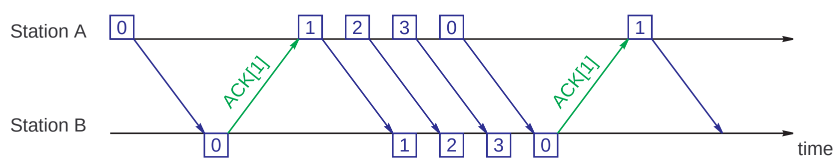
- Receiver get FRAME[i] and sends ACK[$i+1$]
- ACK[$i+1$] lost in transit
- Sender will eventually time-out or get subsequent ACK

Damaged or Lost NACK

- Receiver sends NACK[i], due to error
- NACK[i] lost in transit
- Sender will eventually time-out and retransmit

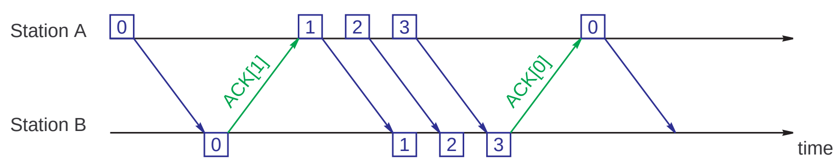
Go-Back-N Window Size

Although similar to sliding window flow control, go-back-n window sizes must be $\leq 2^k - 1$, where k is the sequence field length



$n = 4,\ k = 2$

(Sender does not know if the second ACK[1] is for the first or last FRAME[0])



$n = 3,\ k = 2$

Go-Back-N ARQ Performance

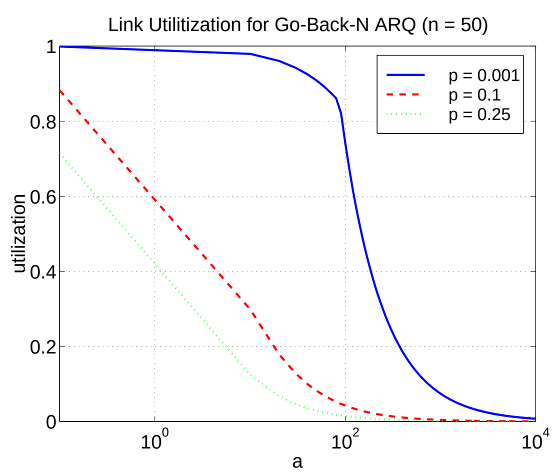
- Same assumptions as stop-and-wait ARQ analysis
- Approximating n is different, since each error may cause multiple frame retransmissions

$$n = E[\text{number of frames required to successfully transmit one frame}]$$
$$= \sum_{i=1}^{\infty} f(i) \cdot p^{i-1}(1-p)$$

where $f(i)$ is the total number of frames transmitted if the original frame must be transmitted i times

- Therefore, the link utilization for go-back-n ARQ is

$$u = \begin{cases} \frac{1-p}{1+2a \cdot p} & n > 2a+1 \\ \frac{n(1-p)}{(2a+1)(1-p+n \cdot p)} & n < 2a+1 \end{cases}$$

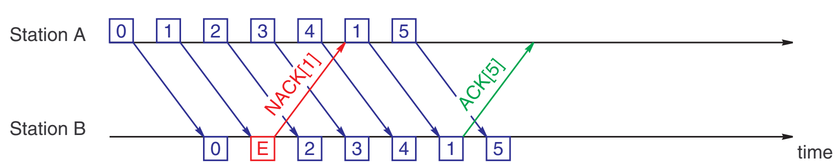


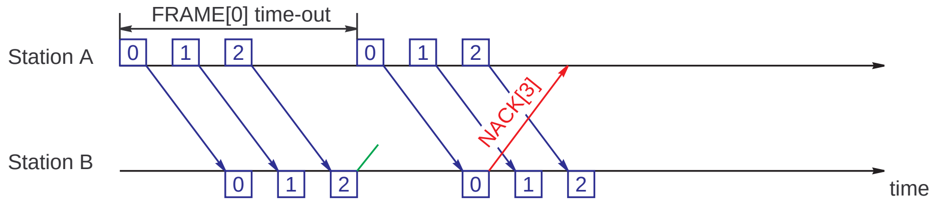
Selective Reject ARQ

Only the specific damaged or lost frame is retransmitted

- If FRAME[i] is lost or damaged, then a NACK[i] is returned
  - Only FRAME[i] is then retransmitted
- Receiving device must *place* frames in correct order
  - Since frames may arrive out of order
- Modifications
  - Receiver continues to accept frames after damaged frame
  - Smaller windows sizes are required, $n \leq 2^{k-1}$

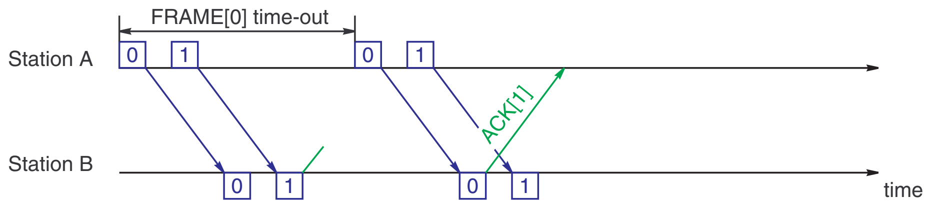
- ACK[i] and NACK[i] still imply the successful receipt of all previous frames
  - Frames after the error frame can not be ACKed until the damaged frame is received





$n = 3,\ k = 2$

(Receiver believes the second FRAME[0] is a new frame, not a repeat)



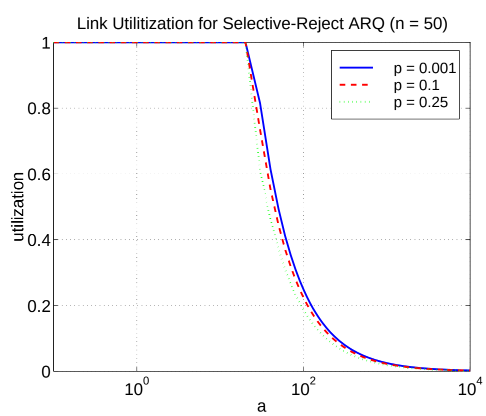
$n = 2,\ k = 2$

(Receiver knows second FRAME[0] is a repeat, since it expects either FRAME[2] or FRAME[3])

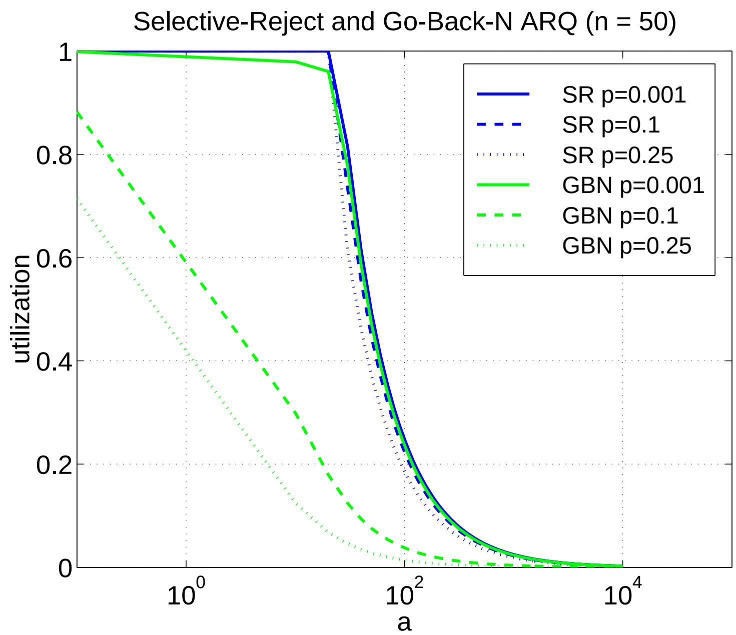
Selective Reject ARQ Performance

- Approximating n is the same as stop-and-wait

$$u = \begin{cases} 1 & n > 2a+1 \\ \frac{n(1-p)}{2a+1} & n < 2a+1 \end{cases}$$



ARQ Utilization Comparison



Go-Back-N and Selective Reject

- As seen in the previous figure, selective-reject yields a higher link utilization
- However, selective-reject is *expensive* to implement
  - Sender needs extra *state* information to retransmitt
  - Receiver needs complex storage and sorting
- Therefore, go-back-n is typically used for implementation