Communication and Networking
Flow Control Basics

D. Richard Brown III

(selected figures from Stallings Data and Computer Communications 10th edition)

Context

So far, we have focused primarily on the **physical layer** and sending signals over a “transmission link”.

We now turn our attention to the **transport layer** and sending data over a “data link”.

Data link control:

1. Frame synchronization: detecting beginning and end of each frame
2. Flow control: ensuring the transmitter does not overwhelm the receiver
3. Error control: dealing with errors in frames
4. Addressing: uniquely identifying transmitters and receivers
5. Distinguishing control information from data
6. Link management: initiation, maintenance, termination of data links

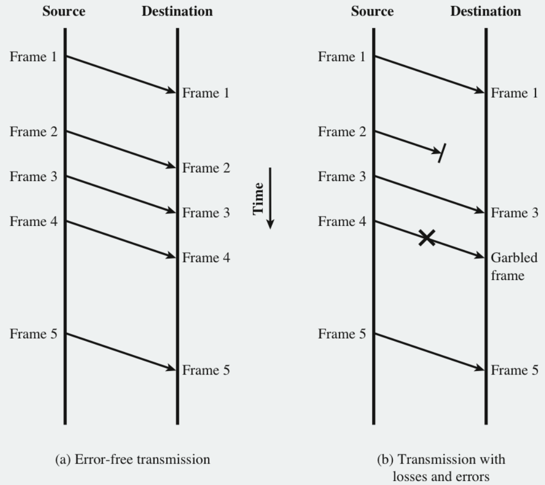


Figure 7.1 Model of Frame Transmission

Flow Control: Motivation and Notation

A receiver typically has a buffer for receiving data. In the absence of flow control, the receiver's buffer may overflow while it is processing data or performing other tasks.

Notation:

t_{prop} : propagation time of data link (assumed to be the same in both directions)

t_{frame} : frame transmission time

t_{proc} : processing time at TX and RX to react to frame or ACK

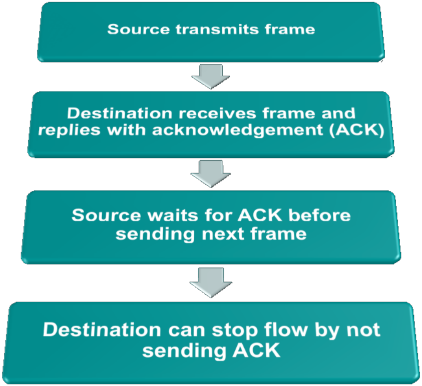
t_{ack} : acknowledgement transmission time

n : number of frames

We want our flow control protocol to be **efficient**. A common measure of efficiency is "link utilization", defined as

$$U = \frac{\text{time spent transmitting data in } n \text{ frames}}{\text{total time required to send } n \text{ frames and receive ACKs}} \le 1.$$

Stop-and-Wait Flow Control

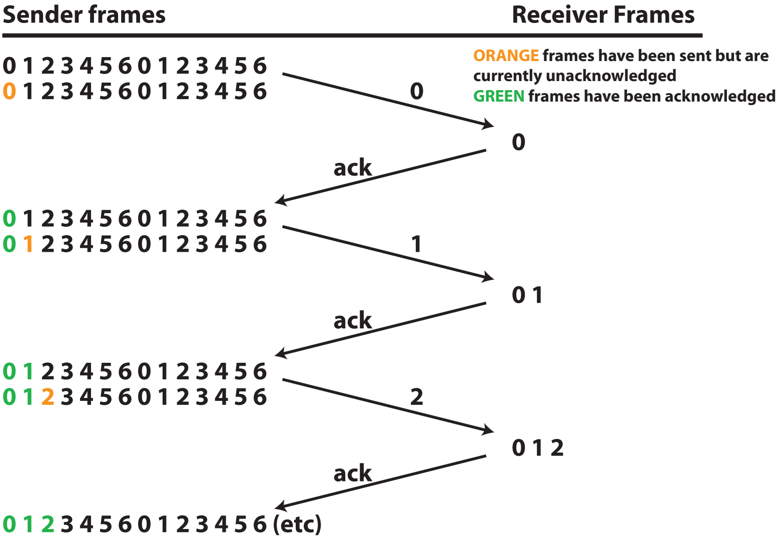


Can be fairly efficient if the transmission uses large frames.

Smaller frames often used, however, since:

- Receive buffer size limited.
- Long frames have higher probability of block error.
- Short frames allow for easier multiplexing with other users.

Stop-and-Wait Flow Control Example



Stop-and-Wait Link Utilization

The total time to send n frames (and receive the acknowledgements) can be expressed as

$$T = n\left(t_{\text{frame}} + t_{\text{prop}} + t_{\text{proc}} + t_{\text{ack}} + t_{\text{prop}} + t_{\text{proc}}\right).$$

Since only nt_{frame} seconds is actually used to transmit the frames, the link utilization is

$$U = \frac{t_{\text{frame}}}{t_{\text{frame}} + t_{\text{ack}} + 2t_{\text{prop}} + 2t_{\text{proc}}}$$

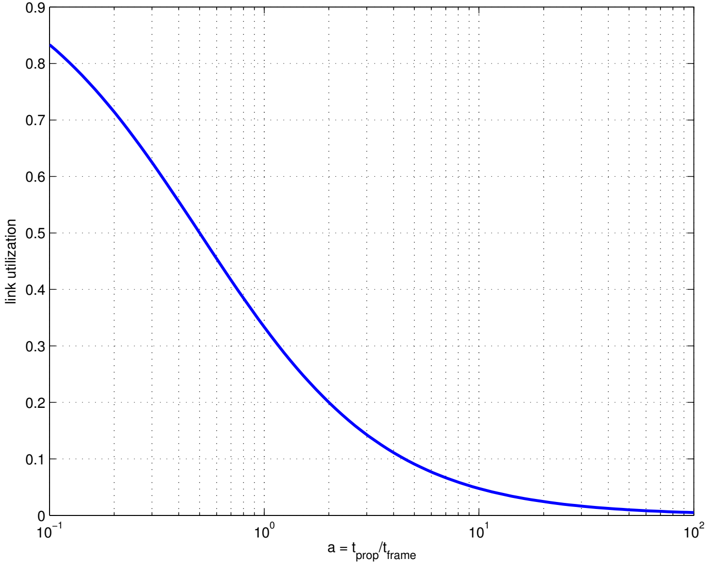
where the overhead of the stop-and-wait flow control protocol is in red.

In many cases, $t_{\text{ack}} \ll t_{\text{frame}}$ and $t_{\text{proc}} \approx 0$, hence we can express the link utilization more simply as

$$U = \frac{t_{\text{frame}}}{t_{\text{frame}} + 2t_{\text{prop}}} = \frac{1}{1+2a}$$

where $a = \frac{t_{\text{prop}}}{t_{\text{frame}}}$.

Stop-and-Wait Link Utilization



Bit Length of a Link

Notation:

R : data rate of link (bits per second)

d : physical length of link (meters)

V : velocity of propagation (meters per second)

We can compute the "bit length" of the link in bits as

$$B = \frac{Rd}{V}$$

where B represents the number of bits present on the link when the transmitter is streaming data at rate R.

Denoting the frame length in bits as L, we can write

$$a = \frac{t_{\text{prop}}}{t_{\text{frame}}} = \frac{d/V}{L/R} = \frac{Rd}{LV} = \frac{B}{L}.$$

Better link utilization when $L \gg B$ (short bit length of link or long frame).

Stop-and-Wait Link Utilization Visualization

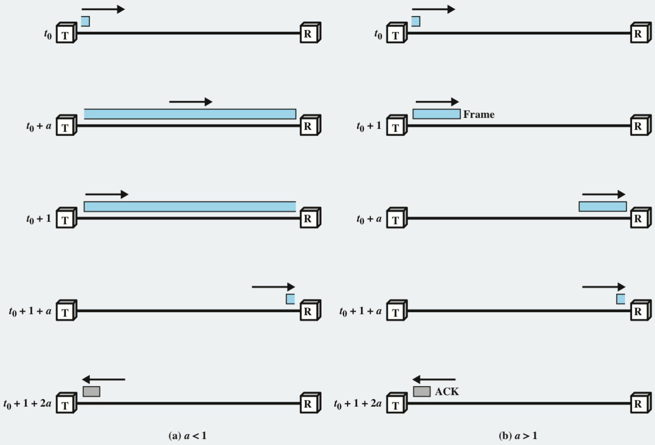


Figure 7.2 Stop-and-Wait Link Utilization (transmission time = 1; propagation time = *a*)

Stop-and-Wait Link Utilization Example 1

Suppose we have a 200 m optical fiber operating at 1 Gbps. The propagation velocity of optical fiber is typically about 2×10^8 m/s. The frame length is 8000 bits (1000 octets).

The bit length of the link can be computed as

$$B = \frac{Rd}{V} = \frac{10^9 \cdot 200}{2 \times 10^8} = 1000 \text{ bits.}$$

The link utilization using stop-and-wait flow control is

$$U = \frac{1}{1+2a} = \frac{1}{1+2B/L} = \frac{1}{1+2000/8000} = \frac{4}{5}$$

which means that the link is being used 80% of the time to transmit data (20% of the time is overhead).

Stop-and-Wait Link Utilization Example 2

Suppose we have a 72000 km satellite link operating at 1 Mbps. The propagation velocity of wireless transmission is close to 3×10^8 m/s. The frame length is 8000 bits (1000 octets).

The bit length of the link can be computed as

$$B = \frac{Rd}{V} = \frac{10^6 \cdot 72 \times 10^6}{3 \times 10^8} = 240 \times 10^3 \text{ bits.}$$

The link utilization using stop-and-wait flow control is

$$U = \frac{1}{1+2a} = \frac{1}{1+2B/L} = \frac{1}{1+(480 \times 10^3)/8000} \approx 0.0164$$

which means that the link is being used approximately 1.6% of the time to transmit data (98.4% of the time is overhead).

Sliding Window Flow Control

Basic idea:

- Improve efficiency (link utilization) by **pipelining** transmissions
- Allow multiple frames to be transmitted without requiring immediate acknowledgement of each frame
- Each frame must have a sequence number
- Sliding window (buffer) of W frames:
  - Transmitter can send up to W frames without ACK
  - ACK (receive ready (RR)) from receiver **can acknowledge multiple frames** and specifies the sequence number of next expected frame
  - Receiver can also ACK frames and halt further transmission (receive not ready (RNR))
  - Normal ACK/RR resumes transmission
- Note that $W = 1$ corresponds to stop-and-wait flow control.

Sliding-Window Flow Control: $W = 7$

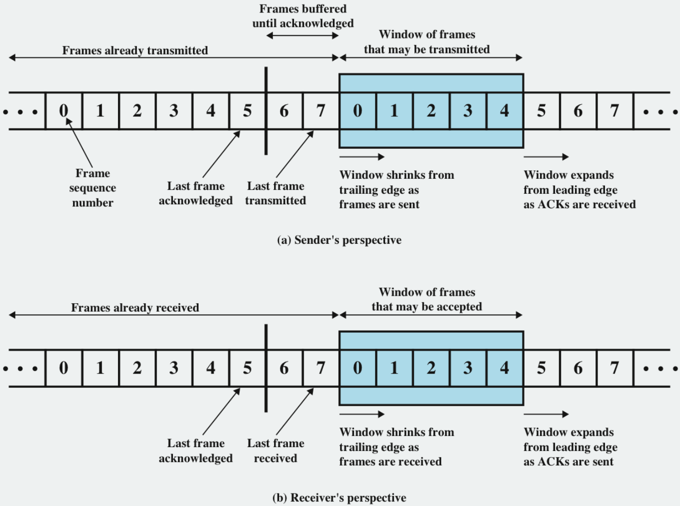


Figure 7.3 Sliding-Window Depiction

Sliding-Window Flow Control: $W = 7$

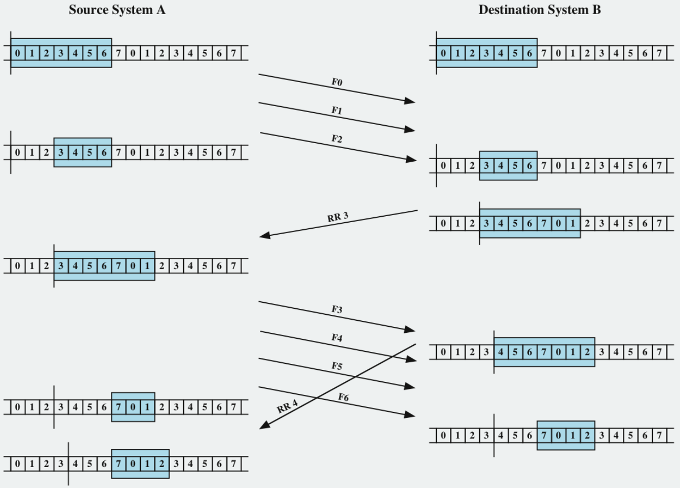
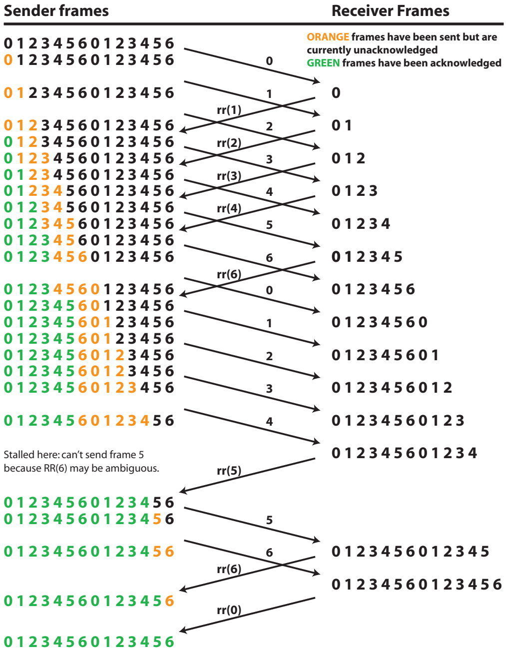


Figure 7.4 Example of a Sliding-Window Protocol


Sender frames
Receiver Frames
ORANGE frames have been sent but are currently unacknowledged
GREEN frames have been acknowledged
0 1 2 3 4 5 6 0 1 2 3 4 5 6
0
1
rr(1)
2
rr(2)
3
rr(3)
4
rr(4)
5
6
rr(6)
0
1
2
3
4
rr(5)
5
6
rr(6)
rr(0)
0
0 1
0 1 2
0 1 2 3
0 1 2 3 4
0 1 2 3 4 5
0 1 2 3 4 5 6
0 1 2 3 4 5 6 0
0 1 2 3 4 5 6 0 1
0 1 2 3 4 5 6 0 1 2
0 1 2 3 4 5 6 0 1 2 3
0 1 2 3 4 5 6 0 1 2 3 4
0 1 2 3 4 5 6 0 1 2 3 4 5
0 1 2 3 4 5 6 0 1 2 3 4 5 6
Stalled here: can't send frame 5 because RR(6) may be ambiguous.

Sliding-Window Link Utilization Analysis (part 1 of 2)

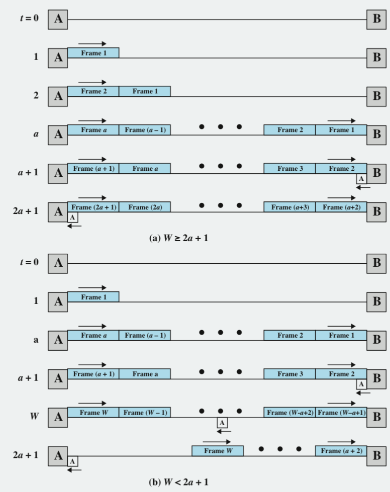


Figure 16.9 Timing of Sliding-Window Protocol

If ACKs can be received before sliding window is exhausted, then A can transmit continuously without interruption. The link utilization in this case is $U = 1$.

Assume negligible processing time and $t_{\rm frame} \gg t_{\rm ack}$. Time to first ACK:

$$T_1 = t_{\rm frame} + t_{\rm prop} + t_{\rm prop} \text{ (seconds)}$$
$$= \frac{L}{R} + 2\frac{d}{V} \text{ (seconds)}$$

Sliding window duration:

$$T_W = \frac{WL}{R} \text{ (seconds)}$$

We have $U = 1$ if

$$T_W \geq T_1 \quad \Leftrightarrow \quad W \geq 2a + 1$$

where $a = \frac{Rd}{LV}$.

Sliding-Window Link Utilization Analysis (part 2 of 2)

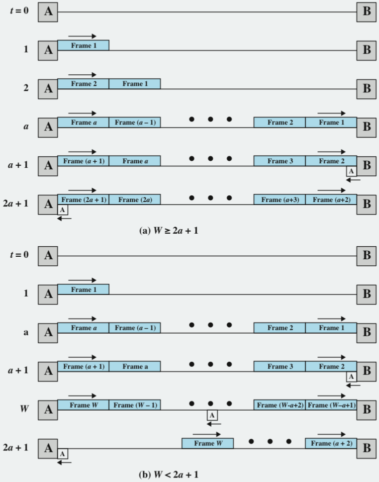


Figure 16.9 Timing of Sliding-Window Protocol

If ACKs are not received until after the sliding window is exhausted, i.e.,

$$W < 2a + 1$$

then A must pause transmission.

The link utilization in this case is

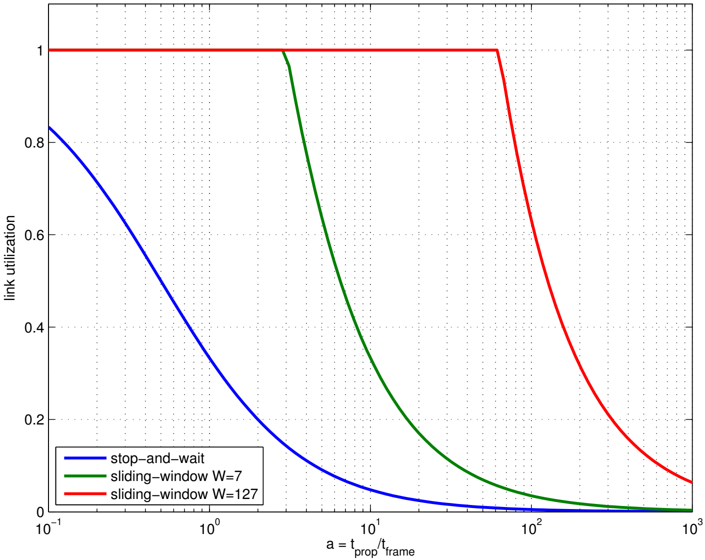
$$\begin{aligned} U &= \frac{T_W}{T_1} \\ &= \frac{WL/R}{L/R + 2d/V} \\ &= \frac{W}{2a+1} \end{aligned}$$

where $a = \frac{Rd}{LV}$.

In general, we have

$$U = \min\left\{\frac{W}{2a+1}, 1\right\}.$$

Sliding-Window Link Utilization



Sliding-Window Link Utilization Example 1

Suppose we have a 200 m optical fiber operating at 1 Gbps. The propagation velocity of optical fiber is typically about 2×10^8 m/s. The frame length is 8000 bits (1000 octets).

The link utilization using sliding-window flow control is

$$\begin{aligned} U &= \min\left\{\frac{W}{1+2a}, 1\right\} \\ &= \min\left\{\frac{W}{1.25}, 1\right\} \\ &= \begin{cases} 1 & W \geq 2 \\ \frac{4}{5} & W = 1. \end{cases} \end{aligned}$$

In other words, $W = 2$ is sufficient to achieve 100% link utilization.

Sliding Window Link Utilization Example 2

Suppose we have a 72000 km satellite link operating at 1 Mbps. The propagation velocity of wireless transmission is close to 3×10^8 m/s. The frame length is 8000 bits (1000 octets).

The link utilization using sliding-window flow control is

$$
\begin{aligned}
U &= \min\left\{\frac{W}{1+2a}, 1\right\} \\
&= \min\left\{\frac{W}{61}, 1\right\} \\
&= \begin{cases} 1 & W \geq 61 \\ \frac{W}{61} & W < 61. \end{cases}
\end{aligned}
$$

In other words, $W = 61$ is sufficient to achieve 100% link utilization. If we go with $W = 7$, we get $\approx 11.5\%$ link utilization, which is not very good (but is better than stop-and-wait).

Final Remarks

- Primary purpose of flow control: allow receiver to control the rate of frame transmissions and avoid buffer overflow
- How? Receiver transmits acknowledgements (ACKs) to sender
- Acknowledgements (RR) permit sender to transmit more packets or tells transmitter to stop (RNR).
- Stop-and-wait flow control
  - Simple but low link utilization, especially if propagation delays are large
- Sliding-window flow control
  - Sequence numbering and occasional ACK/RRs used to improve link utilization
  - More complicated to implement
  - $W = 1$ sliding-window is the same as stop-and-wait
  - Higher values of W typically achieve better link utilization (assuming no frame errors)