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:

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

\( t_{\text{frame}} \): frame transmission time

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

\( t_{\text{ack}} \): 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

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

Sender frames

ORANGE frames have been sent but are currently unacknowledged

GREEN frames have been acknowledged

Receiver Frames

0 1 2 3 4 5 6 0 1 2 3 4 5 6
0 1 2 3 4 5 6 0 1 2 3 4 5 6

ack

0 1 2 3 4 5 6 0 1 2 3 4 5 6
0 1 2 3 4 5 6 0 1 2 3 4 5 6

1

ack

0 1 2 3 4 5 6 0 1 2 3 4 5 6
0 1 2 3 4 5 6 0 1 2 3 4 5 6

2

ack

0 1 2 3 4 5 6 0 1 2 3 4 5 6 (etc)
Stop-and-Wait Link Utilization

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

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

Since only $nt_{\text{frame}}$ 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

The graph illustrates the link utilization as a function of the ratio $a = \frac{t_{prop}}{t_{frame}}$. The x-axis represents the ratio $a$ ranging from $10^{-1}$ to $10^2$, and the y-axis represents the link utilization ranging from 0.9 to 0.0. The curve shows how the link utilization decreases as the ratio $a$ increases.
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 = $a$)

(a) $a < 1$

(b) $a > 1$
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 $2 \times 10^8$ 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 $3 \times 10^8$ m/s. The frame length is 8000 bits (1000 octets).

The bit length of the link can be computed as

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

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: \( W = 7 \)

![Diagram of Sliding-Window Flow Control](image)

**Figure 7.4 Example of a Sliding-Window Protocol**
### Sender frames vs Receiver Frames

<table>
<thead>
<tr>
<th>Sender frames</th>
<th>Receiver Frames</th>
</tr>
</thead>
<tbody>
<tr>
<td>01 23 45 60 12 34 56</td>
<td>01 23 45 60 12 34 56</td>
</tr>
<tr>
<td>ORANGE frames have been sent but are currently unacknowledged</td>
<td></td>
</tr>
<tr>
<td>GREEN frames have been acknowledged</td>
<td></td>
</tr>
</tbody>
</table>

- **rr(1)**
- **rr(2)**
- **rr(3)**
- **rr(4)**
- **rr(5)**
- **rr(6)**

**Stalled here:** Can't send frame 5 because RR(6) may be ambiguous.
Sliding-Window Link Utilization Analysis (part 1 of 2)

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 \( t_{\text{frame}} \gg t_{\text{ack}} \). Time to first ACK:

\[
T_1 = t_{\text{frame}} + t_{\text{prop}} + t_{\text{prop}} \quad \text{(seconds)}
\]

\[
= \frac{L}{R} + 2\frac{d}{V} \quad \text{(seconds)}
\]

Sliding window duration:

\[
T_W = \frac{W L}{R} \quad \text{(seconds)}
\]

We have \( U = 1 \) if

\[
T_W \geq T_1 \iff W \geq 2a + 1
\]

where \( a = \frac{Rd}{LV} \).
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

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

where

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

In general, we have

$$U = \min \left\{ \frac{W}{2a + 1}, 1 \right\}.$$
Sliding-Window Link Utilization

```
link utilization

- stop-and-wait
- sliding-window W=7
- sliding-window W=127

\[ a = \frac{t_{\text{prop}}}{t_{\text{frame}}} \]
```
Suppose we have a 200 m optical fiber operating at 1 Gbps. The propagation velocity of optical fiber is typically about $2 \times 10^8$ m/s. The frame length is 8000 bits (1000 octets).

The link utilization using sliding-window flow control is

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

$$= \min \left\{ \frac{W}{1.25}, 1 \right\}$$

$$= \begin{cases} 1 & W \geq 2 \\ \frac{4}{5} & W = 1. \end{cases}$$

In other words, $W = 2$ is sufficient to achieve 100% link utilization.
Suppose we have a 72000 km satellite link operating at 1 Mbps. The propagation velocity of wireless transmission is close to $3 \times 10^8$ m/s. The frame length is 8000 bits (1000 octets).

The link utilization using sliding-window flow control is

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

$$= \min \left\{ \frac{W}{61}, 1 \right\}$$

$$= \begin{cases} 1 & W \geq 61 \\ \frac{W}{61} & W < 61 \end{cases}.$$

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)