L5: Building Direct Link Networks III

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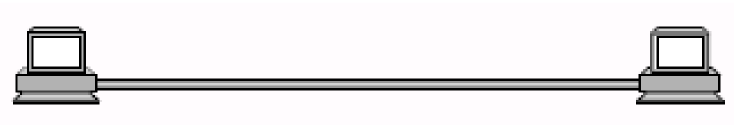
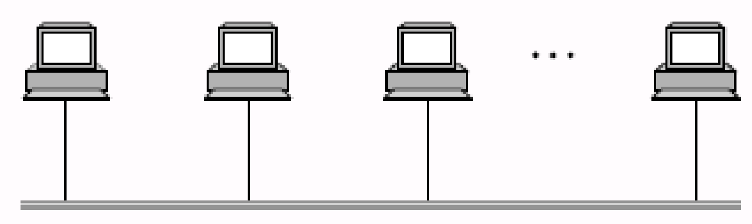
Acknowledgements

- Some pictures used in this presentation were obtained from the Internet
- The instructor used the following references
  - Larry L. Peterson and Bruce S. Davie, Computer Networks: A Systems Approach, 5th Edition, Elsevier, 2011
  - Andrew S. Tanenbaum, Computer Networks, 5th Edition, Prentice-Hall, 2010
  - James F. Kurose and Keith W. Ross, Computer Networking: A Top-Down Approach, 5th Ed., Addison Wesley, 2009
  - Larry L. Peterson's (http://www.cs.princeton.edu/~llp/) Computer Networks class web site

Direct Link Networks

- Types of Networks
  - Point-to-point
  - Multiple access





- Encoding
  - Encoding bits onto transmission medium
- Framing
  - Delineating sequence of bits into messages
- Error detection
  - Detecting errors and acting on them
- **Reliable delivery**
  - **Making links appear reliable despite errors**
- Media access control
  - Mediating access to shared link

Reliable Transmission

- How to make unreliable links appear to be reliable?
- What to do when a receiver detects that the received frame contains an error?

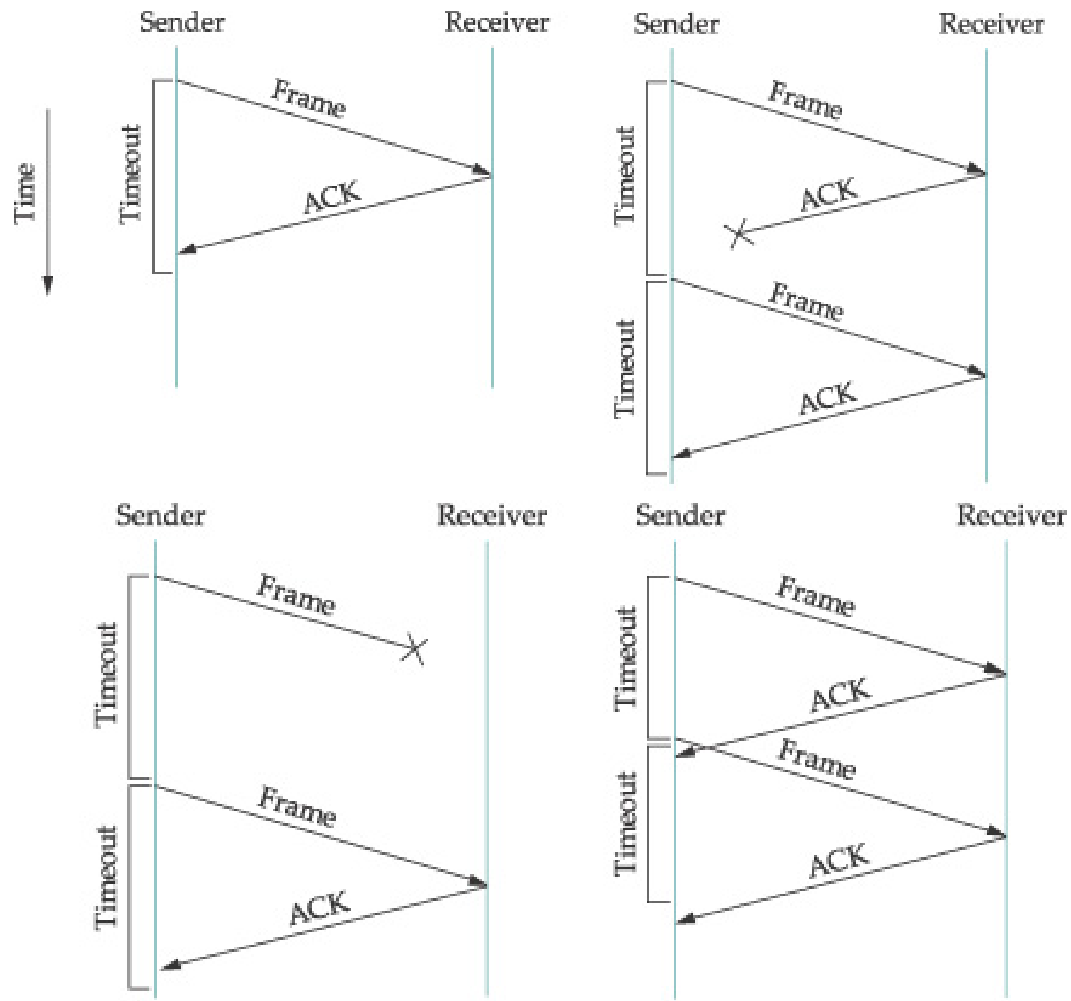
Acknowledgment and Time-Out

- Two fundamental mechanisms to make channels appear to be error-free
  - Acknowledgements (ACK)
  - Time out
- Automatic Repeat Request (ARQ)
  - Stop-and-Wait
  - Sliding Window
- Discuss Stop-and-Wait and Sliding Window protocols in *the context of point-to-point links*

Stop-and-Wait

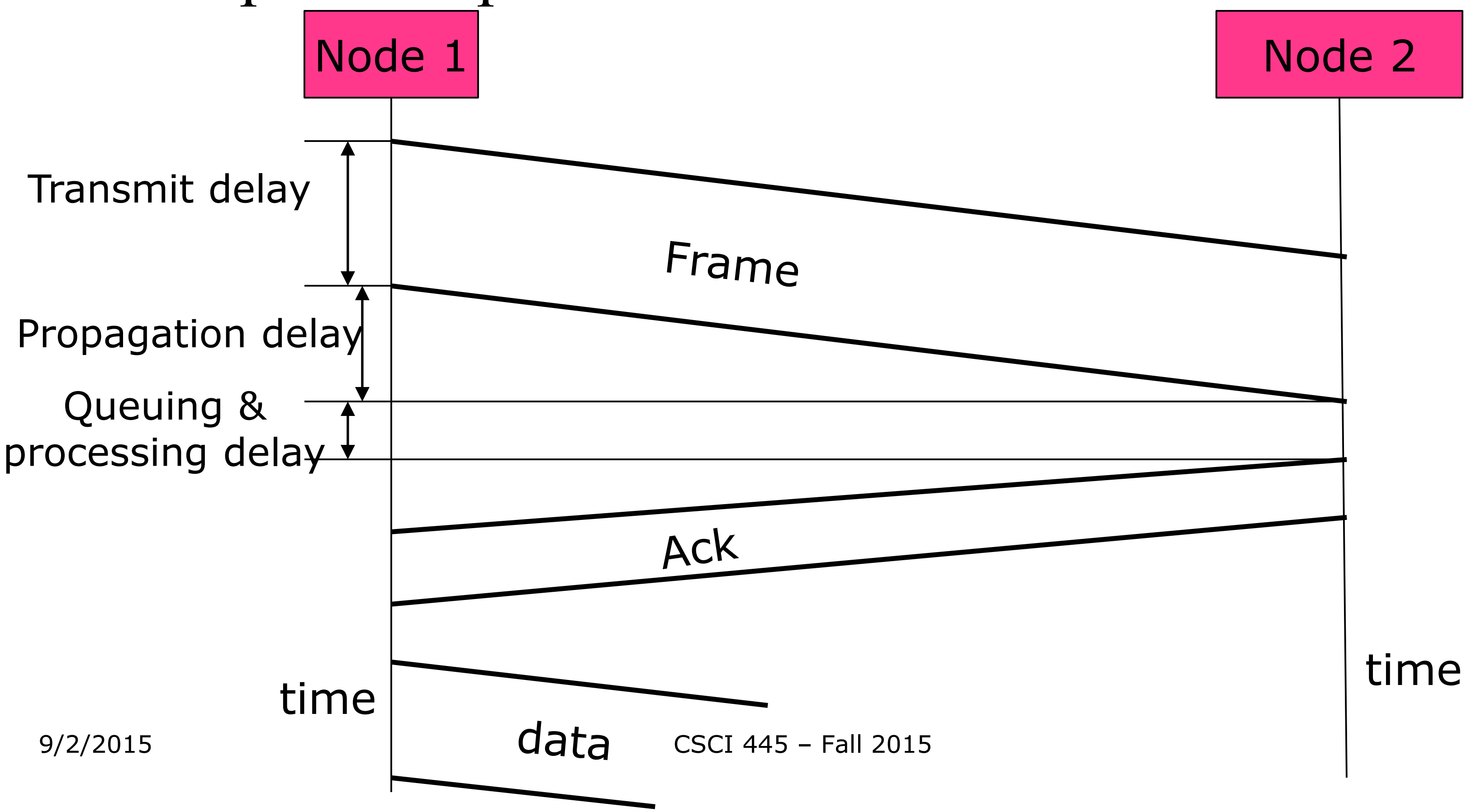
- Sender transmits a frame
- Sender *waits* for an acknowledgement before transmitting the next frame
- If no acknowledgement arrives after a *time-out*, the sender times out and *retransmits* the original frame

Stop-and-Wait



Performance

- Performance analysis for the stop-and-wait protocol with point-to-point links



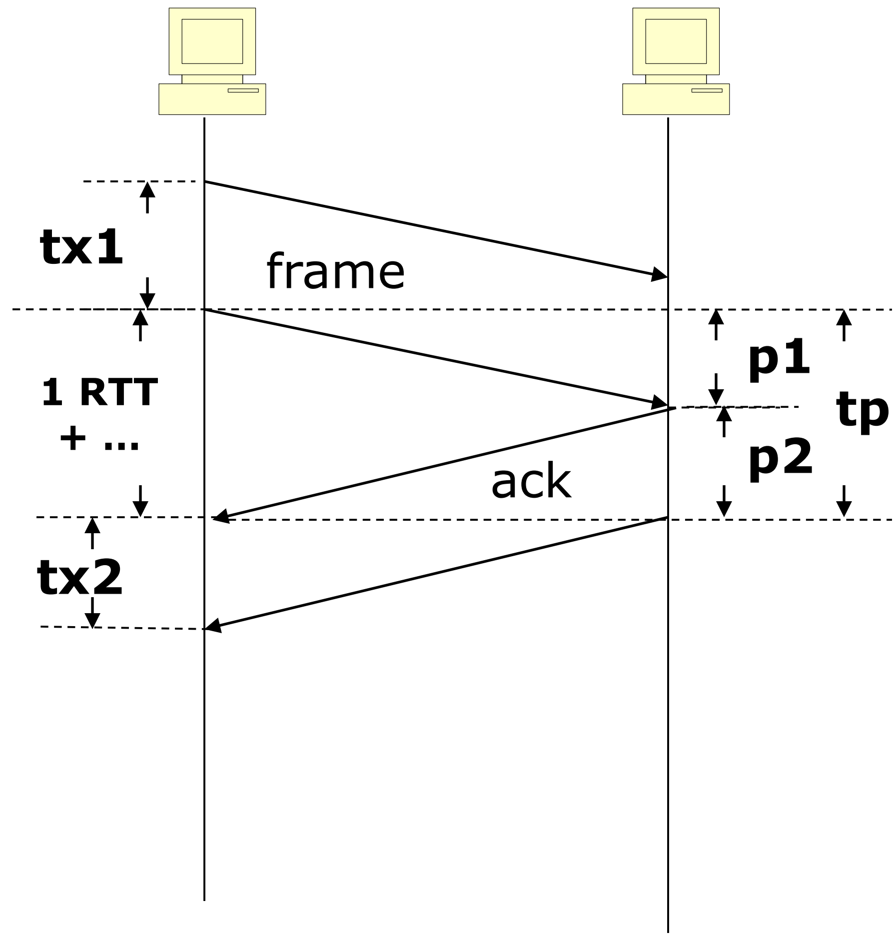
Example

- Link bandwidth: 10 Gbps
- RTT = 40 ms
- Frame size = 1500 bytes
- Acknowledgement size = 64 bytes
- Timeout: 2 × RTT
- Assume processing delay is 0
- Stop-and-Wait protocol: receiver transmits acknowledge frame upon receiving the data frame
- Q: what is the **maximum** throughput (effective bandwidth)?

Throughput

- Q: what is the **maximum** throughput (effective bandwidth)?

- Note: tp = p1 + p2 = 1 RTT
- Transfer time = tx1 + tx2 + tp
- Throughput = Transfer size/Transfer time
- Q: Is this a good protocol?



Timeout?

- How long should the receiver wait?

- Timeout: 2 x RTT or more …

Exercise L5-1

- Data frame size (data) = 1500 bytes
- Acknowledgement frame size (ack) = 64 bytes
- Processing delay is 0
- Stop-and-Wait protocol: *receiver is forced to wait 1 RTT before transmitting acknowledgement frame after having received data frame*
- Draw timing-diagram first, and then compute throughputs and link bandwidth utilization for *one* of the following,
  - Dial-up
    - RTT = 87 μs; Link bandwidth: 56 Kbps
  - Wireless LAN
    - RTT = 0.33 μs; Link bandwidth: 54 Mbps
  - Satellite
    - RTT = 230 ms; Link bandwidth: 45 Mbps

Stop-and-Wait

- Advantage
  - Simple
  - Achieve reliable transmission on non-reliable medium
- Disadvantage
  - Performance is POOR
  - Could you intuitively give an explanation why the performance is POOR?

Stop-and-Wait

- Does not keep the pipe full!
  - Q: How much data are needed to keep the pipe full?
  - Product of Delay × Link Bandwidth
    - $(1 \times RTT) \times 10$ Gbps = 1×40 ms $\times$ 10 Gbps = 400 Mb = 50 MB
    - 50 MB/1500 bytes = 33333 frames
  - 1500 bytes << the product ➔ low link utilization

Link Type	Bandwidth (Typical)	Distance (Typical)	Round-trip Delay	Delay × BW
Dial-up	56 Kbps	10 km	87 μs	5 bits
Wireless LAN	54 Mbps	50 m	0.33 μs	18 bits
Satellite	45 Mbps	35,000 km	230 ms	10 Mb
Cross-country fiber	10 Gbps	4,000 km	40 ms	400 Mb

Q: How to keep the pipe full?

How to keep the “pipe” full?

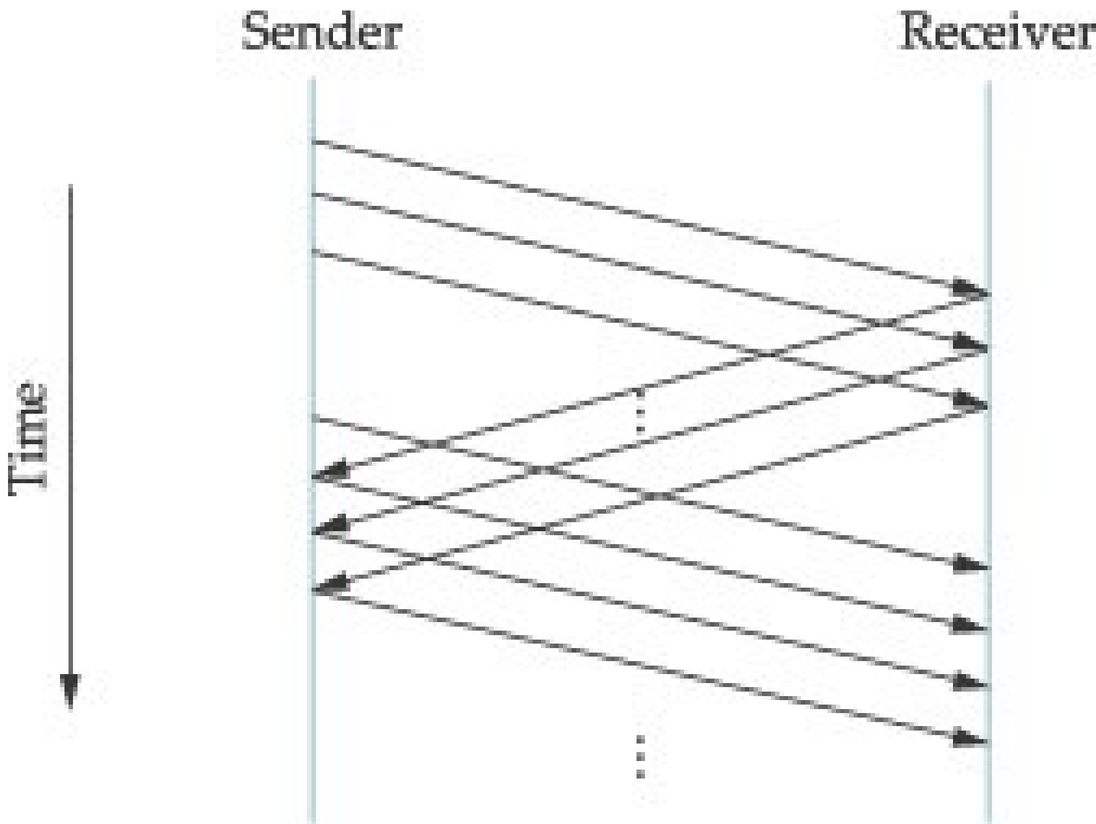
- The amount of data needed to keep the pipe full
- Example
  - Link bandwidth: 10 Gbps
  - RTT = 40 ms
  - Stop-and-Wait protocol: receiver transmitting acknowledgement frame upon receiving data frame
  - Data frame size = 1500 bytes
- Delay × Bandwidth = ?
- How many frames that needed to keep the pipe full?
- What is the throughput?

How to keep the “pipe” full?

- Free discussion

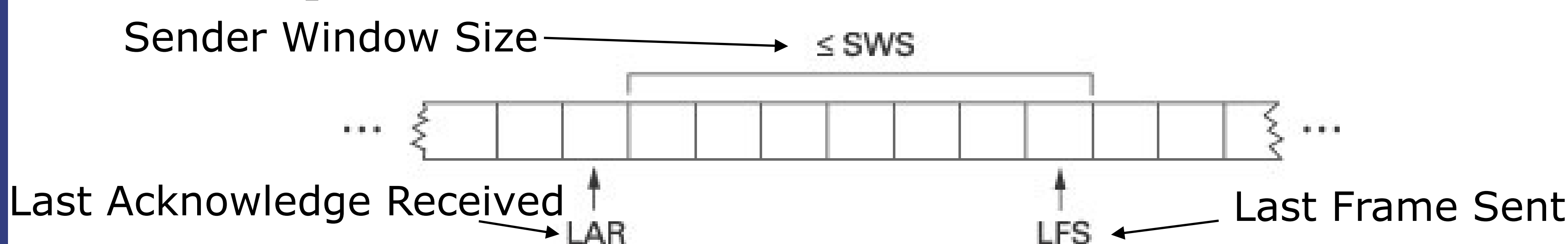
Sliding Window Algorithm

- Allow multiple unacknowledged frames (send a few frames in a batch) ➔ try to fill the pipe
- Define a time window (threshold, or upper bound) on unacknowledged frames
  - Sending window
  - Receiving window
- Have variations



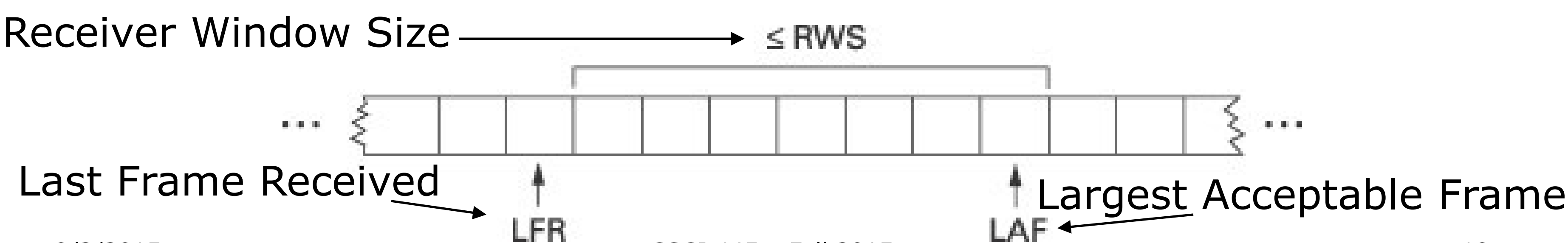
Sliding Windows Algorithm: Sender

- Assign sequence number to each frame (SeqNum)
- Maintain three state variables:
  - Send Window Size (SWS)
  - Last Acknowledgment Received (LAR)
  - Last Frame Sent (LFS)
- Maintain invariant: LFS - LAR <= SWS
- Advance LAR when ACK arrives
- Buffer up to SWS frames

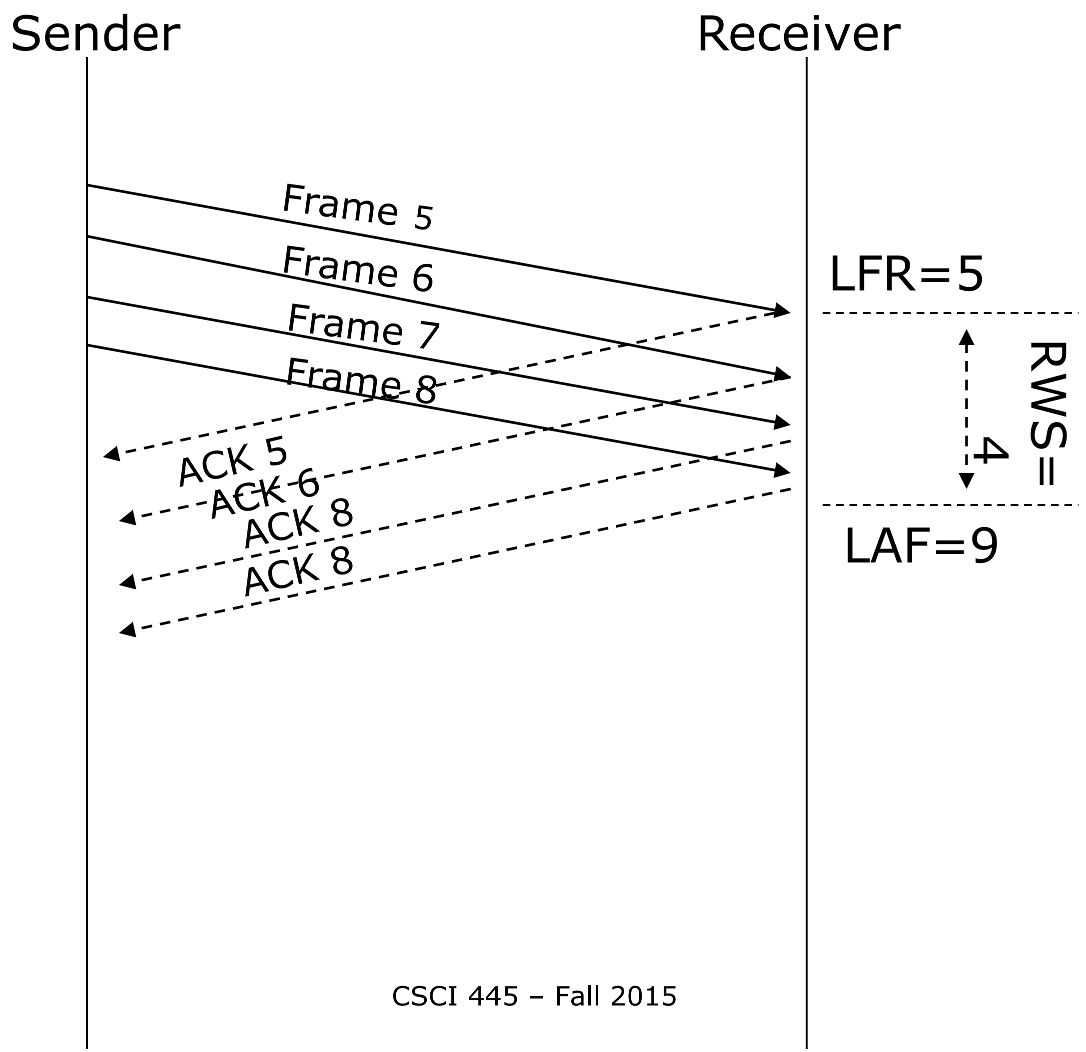


Sliding Windows Algorithm: Receiver

- Maintain three state variables
  - Receive Window Size (RWS)
  - Largest Acceptable Frame (LAF)
  - Last Frame Received (LFR)
- Maintain invariant: LAF - LFR <= RWS
- $\text{Frame}_{\text{SeqNum}}$ arrives:
  - if LFR < SeqNum < = LAF, accept the frame
  - if SeqNum < = LFR or SeqNum > LAF, discard the frame
- SeqNumToAck: largest sequence number not yet acknowledged
- ACK is ***cumulative*** → ACK all frames with less or equal SeqNum

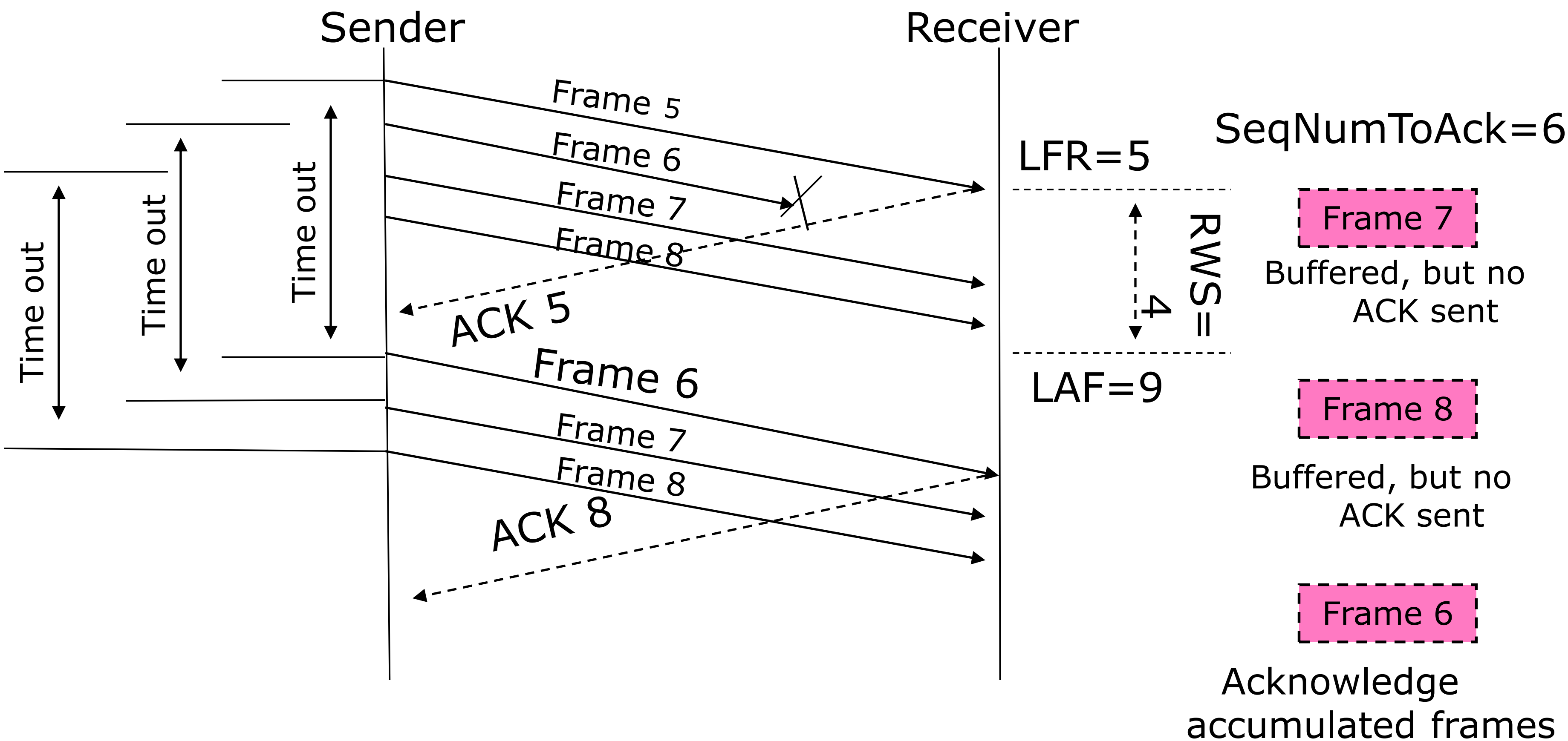


Example: No Frame "Loss"



Example: Frame "Loss"

- Assume that sender does not have more data frame to transmit



Sliding Window Algorithm: SWS and RWS

- SWS should be determined by the product of delay × bandwidth
- RWS does not have to be equal to SWS
  - RWS = 1, does not buffer any frames that arrive out of order
  - RWS > SWS is meaningless, since it is impossible for more than SWS frames to arrive out of order

Examples

- Consider following sliding window algorithm
  - Caution: Parameters chosen for demos only. In reality they need to be carefully chosen. Check footnote in page 108.
  - Timeout = $2 \times$ RTT
  - SWS (send window size) = 4
    - Determined by delay $\times$ bandwidth. Again check footnote in page 108.
  - RWS (receive window size) = 4
- Show timing diagrams for the following scenarios
  - Frame 5 lost
  - Frame 6 lost
  - Frames 5-8 lost
  - ACK 6 lost
  - ACK 8 lost and no more frames to send (for an extended period of time)

Sliding Window Algorithm: Implementation – Data Structures

```
typedef u_char  SwpSeqno;
typedef struct {
    SwpSeqno  SeqNum;   /* sequence number of this frame */
    SwpSeqno  AckNum;   /* ack of received frame */
    u_char    Flags;    /* up to 8 bits worth of flags */
} SwpHdr;
```

```
typedef struct {
    /* sender side state: */
    SwpSeqno    LAR;        /* seqno of last ACK received */
    SwpSeqno    LFS;        /* last frame sent */
    Semaphore   sendWindowNotFull;
    SwpHdr      hdr;        /* pre-initialized header */
    struct sendQ_slot {
        Event   timeout;
                /* event associated with send-timeout */
        Msg     msg;
    } sendQ[SWS];

    /* receiver side state: */
    SwpSeqno    NFE;
                /* seqno of next frame expected */
    struct recvQ_slot {
        int     received; /* is msg valid? */
        Msg     msg;
    } recvQ[RWS];
} SwpState;
```

Sliding Window Algorithm: Implementation – Sending

```
static int
sendSWP(SwpState *state, Msg *frame)
{
    struct sendQ_slot *slot;
    hbuf[HLEN];

    /* wait for send window to open */
    semWait(&state->sendWindowNotFull);
    state->hdr.SeqNum = ++state->LFS;
    slot = &state->sendQ[state->hdr.SeqNum % SWS];
    store_swp_hdr(state->hdr, hbuf);
    msgAddHdr(frame, hbuf, HLEN);
    msgSaveCopy(&slot->msg, frame);
    slot->timeout = evSchedule(swpTimeout, slot,
        SWP_SEND_TIMEOUT);
    return send(LINK, frame);
}
```

Sliding Window Algorithm: Implementation – Receiving (1)

```
static int
deliverSWP(SwpState state, Msg *frame)
{
    SwpHdr   hdr;
    char     *hbuf;

    hbuf = msgStripHdr(frame, HLEN);
    load_swp_hdr(&hdr, hbuf)
    if (hdr->Flags & FLAG_ACK_VALID)
    {
        /* received an acknowledgment---do SENDER side */
        if (swpInWindow(hdr.AckNum, state->LAR + 1,
            state->LFS))
        {
            do
            {
                struct sendQ_slot *slot;
                slot = &state->sendQ[++state->LAR % SWS];
                evCancel(slot->timeout);
                msgDestroy(&slot->msg);
                semSignal(&state->sendWindowNotFull);
            } while (state->LAR != hdr.AckNum);
        }
    }
```

Sliding Window Algorithm: Implementation – Receiving (2)

```
if (hdr.Flags & FLAG_HAS_DATA)
{
    struct recvQ_slot *slot;

    /* received data packet---do RECEIVER side */
    slot = &state->recvQ[hdr.SeqNum % RWS];
    if (!swpInWindow(hdr.SeqNum, state->NFE,
        state->NFE + RWS - 1))
    {
        /* drop the message */
        return SUCCESS;
    }
    msgSaveCopy(&slot->msg, frame);
    slot->received = TRUE;
```

```
if (hdr.SeqNum == state->NFE)
{
    Msg m;

    while (slot->received)
    {
        deliver(HLP, &slot->msg);
        msgDestroy(&slot->msg);
        slot->received = FALSE;
        slot = &state->recvQ[++state->NFE % RWS];
    }
    /* send ACK: */
    prepare_ack(&m, state->NFE - 1);
    send(LINK, &m);
    msgDestroy(&m);
}
}
return SUCCESS;
}
```

Exercise L5-2

- Draw a timeline diagram for the sliding window algorithm with SWS=RWS=3 frames in the following two situations (draw two time diagrams for each situation). Use a timeout interval of $2 \times$ RTT
  - Frame 4 is lost
  - Frame 4-6 are lost

Discussion

- Alternatives or improvement
  - Negative Acknowledgement (NAK)
  - Selective Acknowledgement
- Finite sequence numbers and sliding window
- Frame order and flow control

Summary

- Reliable delivery
  - Timeout and Acknowledgement
- Stop-and-Wait
- Sliding Window
- Idea: keep the pipe full
  - Many different algorithms exist, e.g., concurrent logical channels
- How to implement?
  - Consult the book