CSCI-1680
Transport Layer II

Data over TCP: Flow Control

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Based partly on lecture notes by Rodrigo Fonseca, David Mazières, Phil Levis, John Jannotti
TCP Gearup I **TONIGHT** (10/26) 5-7pm, CIT368
- How the project works, how to think about sockets
- Stuff you need for milestone 1

TCP milestone 1: Schedule on/before Thursday, November 2
- Email later today for signups

HW2: Due Mon, Oct 30
- Last problem helpful for milestone 1
The story so far

Stop and Wait: Simplest TCP sender/receiver
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Stop and Wait: Simplest TCP sender/receiver

Key features
- SEQ/ACK numbers denote where sender/receiver are in data stream
- Only one segment is “in flight” at a time
Warmup: Stop and Wait

What are the values for the SEQ and ACK fields?

conn.Write(“hello_world”)
What are the values for the SEQ and ACK fields?

Key features
- SEQ: Position of this segment in the data stream
- ACK: Next sequence number the receiver expects to receive (ACK N == “I have up to (N – 1)”)

conn.Write(“hello_world”)
Warmup: Stop and Wait

What are the values for the SEQ and ACK fields?

```java
conn.Write("hello_world")
```

Key features
- **SEQ**: Position of this segment in the data stream
- **ACK**: Next sequence number the receiver expects to receive (ACK N == “I have up to (N – 1)”)  

**Advertised window**: how much space the receiver has left in its receive buffer

=> **Window (WIN) field in TCP header**

(TCP Handshake)

<table>
<thead>
<tr>
<th>SEQ</th>
<th>ACK</th>
<th>WIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>89</td>
</tr>
</tbody>
</table>

- SEQ: Position of this segment in the data stream
- ACK: Next sequence number the receiver expects to receive (ACK N == “I have up to (N – 1)”)
Topics for today

- Flow control: Sliding window
- Computing RTO
- Connection termination
TCP and buffering

Recall: TCP stack responsibilities

• Sender: breaking application data into segments
• Receiver: receiving segments, reassembling them in order
TCP and buffering

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• Sender: breaking application data into segments
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TCP stack needs to buffer data for both parts
• Sender: data waiting to be sent, not yet ACK’d
• Receiver: data not yet read by app, out-of-order segments
TCP and buffering

Recall: TCP stack responsibilities
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TCP stack needs to buffer data for both parts
- **Sender**: data waiting to be sent, not yet ACK’d
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Remember: in reality, both sides can send and receive! => All sockets have both a send and receive buffer
Sliding window: in abstract terms

- Window of size $w$
- Can send at most $w$ packets before waiting for an ACK

Goals
- Network “pipe” always filled with data
- ACKs come back at rate data is delivered => “self-clocking”
Sender example
Receiver example
Flow Control: Sender

Invariants

- LastByteSent – LastByteAcked <= AdvertisedWindow
- EffectiveWindow = AdvertisedWindow – (BytesInFlight)
- LastByteWritten – LastByteAcked <= MaxSendBuffer

Useful Sliding Window Terminology:
RFC 9293, Sec 3.3.1
Flow control: receiver

- Can accept data if space in window
- Available window = BufferSize– ((NextByteExpected-1) - LastByteRead)

On receiving segment for byte S
- if s is outside window, ignore packet
- if s == NextByteExpected:
  - Deliver to application (Update LastByteReceived)
  - If next segment was early arrival, deliver it too
- If s > NextByteExpected, but within window
  - Queue as early arrival

Send ACK for highest contiguous byte received, available window
Unfilled buffer

Data received, but not acknowledged

Data received, acknowledged and delivered to application

Sequence numbers (Circumference = 0 to 2^32 slots)

Data received, acknowledged, but not yet delivered to application

Initial sequence number

Receiver's window (Allocation buffer)
Up to 2^16-1 slots

Window shifts

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Data received, acknowledged and delivered to application

Data received, acknowledged, but not yet delivered to application

Unfilled buffer

Window shifts

Receiver's window (Allocation buffer)
Up to 2^16-1 slots
Some Visualizations

• Normal conditions: https://www.youtube.com/watch?v=zY3Sxvj8kZA

• With packet loss: https://www.youtube.com/watch?v=lk27yiITOvU
What happens if the receiving app never reads from its buffer?
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- Receive buffer fills up \(\Rightarrow\) Advertised window drops to 0
- Send buffer fills up
- Eventually, sending app can’t send anymore
What happens if the receiving app never reads from its buffer?

Problem: need a way for sender to know when space is available again!
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Problem: need a way for sender to know when space is available again!

Resolution: zero window probing

– Sender periodically sends 1-byte segments
– Receiver sends back ACK with advertised window (even if it has no room for segment
What happens if the receiving app never reads from its buffer?

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Resolution: zero window probing

– Sender periodically sends 1-byte segments
– Receiver sends back ACK with advertised window (even if it has no room for segment
– Sender can resume sending when win != 0 (preferably when win >= MSS)
TCP State Diagram

1. **CLOSED** (Start)
   - SYN/SYN+ACK
   - CONNECT/SYN

2. **LISTEN**
   - SYN/SYN+ACK
   - SEND/SYN

3. **SYN SENT**
   - SYN+ACK/ACK
   - SYN+ACK/ACK (Simultaneous open)
   - SYN+ACK/ACK (Step 3 of the 3-way-handshake)

4. **SYN RECEIVED**
   - SYN/SYN+ACK
   - RST/-
   - SYN/SYN+ACK (Simultaneous open)

5. **ESTABLISHED**
   - Data exchange occurs
   - SYN+ACK/ACK
   - SYN+ACK/ACK (Step 3 of the 3-way-handshake)

6. **FIN WAIT 1**
   - FIN+ACK/ACK
   - FIN+ACK/ACK

7. **CLOSING**
   - FIN+ACK/ACK
   - ACK/-
   - FIN+ACK/ACK

8. **TIME WAIT**
   - FIN+ACK/ACK
   - FIN+ACK/ACK

9. **LAST ACK**
   - FIN+ACK/ACK
   - FIN+ACK/ACK

10. **CLOSE WAIT**
    - FIN+ACK/ACK
    - FIN+ACK/ACK

11. **FIN WAIT 2**
    - FIN+ACK/ACK
    - FIN+ACK/ACK

12. **CLOSED**
    - FIN+ACK/ACK
    - FIN+ACK/ACK

13. **TIME WAIT**
    - FIN+ACK/ACK
    - FIN+ACK/ACK

14. **CLOSED**
    - FIN+ACK/ACK
    - FIN+ACK/ACK

15. **TIME WAIT**
    - FIN+ACK/ACK
    - FIN+ACK/ACK

16. **CLOSED**
    - FIN+ACK/ACK
    - FIN+ACK/ACK

17. **TIME WAIT**
    - FIN+ACK/ACK
    - FIN+ACK/ACK

18. **CLOSED**
    - FIN+ACK/ACK
    - FIN+ACK/ACK

**Additional States:**
- **Active CLOSE**
- **Passive CLOSE**
- **Go back to start**

**Events:**
- Unusual event: client/receiver path, server/sender path
- Connect event: SYN/ACK
- Disconnect event: RST/-
- Timeout
- Time out
- Close/ active
- Close/ passive
How do ACKs work?

- ACK contains *next expected sequence number*
- Sender: if one segment is missed but new ones received, send duplicate ACK
- Receiver retransmits when:
  - Receive timeout (RTO) expires
  - Possibly other conditions, for certain TCP variants (eg. 3 dup ACKs)
- How to set RTO?
What’s a good timeout value?
- 0.5s? 1s? 0.01s?
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=> How long should it take a packet to arrive at other side?
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⇒ How long should it take a packet to arrive at other side?

1RTT!

=> Can measure RTT, use to set RTO
Computing RTO

Strategy: *measure* expected RTT based on ACKs received

- Use exponentially weighted moving average (EWMA)
Computing RTO

Strategy: *measure* expected RTT based on ACKs received

Use exponentially weighted moving average (EWMA)

- RFC793 version ("smoothed RTT"):
  
  \[
  \text{SRTT} = (\alpha \times \text{SRTT}_{\text{Last}}) + (1 - \alpha) \times \text{RTT}_{\text{Measured}} \\
  \text{RTO} = \max(\text{RTO}_{\text{Min}}, \min(\beta \times \text{SRTT}, \text{RTO}_{\text{Max}}))
  \]

  \[
  \alpha = \text{"Smoothing factor"}: \ 0.8 - 0.9 \\
  \beta = \text{"Delay variance factor"}: \ 1.3 - 2.0 \\
  \text{RTO}_{\text{Min}} = 1 \text{ second}
  \]

RFC793, Sec 3.7
RFC6298 (slightly more complicated, also measures variance)
Using the RTO timer

**Recommended by RFC6298**

- Maintain ONE timer per connection
- When segment is sent => set timer to expire after $t_{RTO}$
- When ACK is received with new data, reset the timer
Using the RTO timer

Recommended by RFC6298

• Maintain ONE timer per connection
• When segment is sent => set timer to expire after $t_{RTO}$
• When ACK is received with new data, reset the timer

When the timer expires:

• Retransmit earliest unacknowledged segment
• $RTO = 2 \times RTO$ (up to some max)
• If no data after N retransmissions => give up, terminate connection
This is only the beginning...

• Problem 1: what if ACK is for a retransmitted segment?
  – Solution: don’t update RTT if segment was retransmitted

• Problem 2: RTT can have high variance
  – Initial implementation doesn’t account for this (modern version, RFC6298)
  – Congestion control: modeling network load