

CS4450

Computer Networks: Architecture and Protocols

Lecture 20 Reliable Transport

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Announcements

- **Prelim**

- We will have prelim on 30th of April and 1st of May
- Exam released on canvas on the 30th at 00:01 AM ET
 - You can start working whenever you want
 - Scanned copies to be submitted by 1st of May, 11:59AM ET
 - Overall 48 hours to finish the exam, submit the copies
- Please let us know immediately if there is an issue with this

- **We will post a practice prelim (and solutions) by Thursday**

- However, its for practice only; the main prelim may be different

Goal of Today's Lecture

- **Understanding reliable transport conceptually**
 - What are the fundamental aspects of reliable transport
- **Back to architectural principles for one lecture**
- The goal is not to understand TCP
 - TCP involves lots of detailed mechanisms, covered later
- Ground rules for discussion
 - No mention of TCP
 - No mention of detailed practical issues
 - Focus only on “ideal” world of packets and links

Decisions and Their Principles

- How to break system into modules?
 - Dictated by layering
- Where are modules implemented?
 - Dictated by End-to-End Principle
- Where state is stored?
 - Dictated by fate-sharing

Today We Design Reliable Delivery

- The end-to-end principle tells us?
 - Put reliability in the end-host, not the network
- Layering dictates putting reliability in what layer?
 - Above network layer
 - L4 focusses on process-to-process delivery (“flow”)
- Fate sharing tells us?
 - Keep all reliability state in ends, not in network

Best Effort Service (L3)

- Packets can be lost
- Packets can be corrupted
- Packets can be reordered
- Packets can be delayed
- Packets can be duplicated
- ...

**How can you possibly make anything work
with such a service model?**

Challenge For Today

- Building a stack that supports reliable transfer
 - So that individual applications don't need to deal with packet losses, etc.
- What mechanisms can we put in the transport layer to provide reliability?
- Reliability is focused on single “flow”
 - Flow: stream of packets between two **processes**
 - **Usually defined using the 5-tuple:**
 - (sourceIP, destIP, sourcePort, destPort, protocol)

Four Goals for Reliable Transfer

- **Correctness**
 - To be defined
- **“Fairness”**
 - Every flow must get a fair share of network resources
- **Flow Performance**
 - Latency, jitter, etc.
- **Utilization**
 - Would like to maximize bandwidth utilization
 - If network has bandwidth available, flows should be able to use it!

Start With Transfer of a Single Packet

- We can later worry about larger files, but in the beginning it is cleaner to focus on this simple case

Correctness Condition

- Routing had a clean correctness condition
- **We want same kind of “if and only if” characterization of “correct” reliable transport designs**
- This condition is **for the design to be correct**, not the best performant
- One obvious requirement:
 - Transport never claims to have delivered data that wasn't delivered...
- But we need more than that. What?

Correctness Condition?

- How about: “Packet is always delivered to receiver”?
- i.e., Transport is reliable if and only if packets are always delivered to the receiver...
- Isn't that simple?

WRONG!

- **What if network is partitioned?**
 - Partitioned means that the network is broken into two or more disconnected components...
- We can't claim a transport design is incorrect if it doesn't work in a partitioned network!
 - After all, there is no way to reach the destination!

Correctness Condition?

- Packet is delivered to receiver if and only if its possible to deliver packet

WRONG!

- If the network is only available at one instant of time, only an Oracle would know when to send
- **We can't claim a transport design is incorrect if it doesn't know the unknowable...**
- So we need to focus on what the transport design is trying to do, not what it actually accomplishes

Correctness Condition?

- Resend packet if and only if the previous transmission was lost or corrupted
- This is better because it refers to:
 - what the design does (which it can control)
 - not whether it always succeeds (which it can't)

WRONG!

- Impossible
 - “Coordinated Attack” over an unreliable network
- Consider two cases:
 - Packet delivered; all packets from receiver are dropped
 - Packet dropped; all packets from receiver are dropped
- They are indistinguishable to sender
 - In both cases, packet was sent, and no feedback at all
 - **Does it resend, or not?**

Correctness Condition?

- Packet is always resent if the previous transmission was lost or corrupted
- Packet **may** be resent at other times
- Note:
 - This invariant gives us a simple criterion for deciding if an implementation is correct
 - Efficiency and simplicity are separate criteria

Almost Right!

- What's wrong with it?
- An implementation that never sent the packet at all is reliable according to the definition.

Complete Correctness Condition

- A transport mechanism is “reliable” if and only if
 - (a) It resends all dropped or corrupted packets
 - (b) It attempts to make progress
- Making progress means:
 - **If there is data to send, transport eventually attempts to send data**
 - Very important: “eventually attempts”!
 - It should not be blocked for ever
 - And, it may not succeed, but it must attempt
 - Example: If there are ten packets to send, transport can’t just send the first five and then stop **for ever**

Complete Correctness Condition

- A transport mechanism is “reliable” if and only if
 - (a) It resends all dropped or corrupted packets
 - (b) It attempts to make progress
- **Sufficient (“if”)**: transport algorithm will keep trying to deliver packets that have not yet reached the destination
- **Necessary (“only if”)**: if it ever lets a packet go undelivered without trying again, or never tries to send a packet when all others have been delivered, it isn’t reliable

Note!

- A transport mechanism can “give up”, but must announce this to application
- If the transport mechanism has tried for some period to deliver the data, and has not succeeded:
 - It might decide that it is better to give up
 - And applications can reinitiate data transfer
 - That is allowed...
- **But it can never falsely claim to have delivered a packet**

We have Correctness Condition

- How do we achieve it?
- Focus on single-packet solutions

Four Goals for Reliable Transfer

- **Correctness**
- **“Fairness”**
 - Every flow must get a fair share of network resources
- **Flow Performance**
 - Latency, jitter, etc.
- **Utilization**
 - Would like to maximize bandwidth utilization
 - If network has bandwidth available, flows should be able to use it!

Solution v1

- **Send the packet as often and fast as possible...**
- Is it correct
 - No.
 - Why?
 - The “if” condition is not satisfied:
 - (a) Transport must **attempt to make progress**
 - No way to check whether the packet was dropped or corrupted
 - So, must continue sending the same packet
 - Will never make progress on other flows (from same source)

What's missing?

- Feedback from receiver!
- If receiver does not respond, no way for sender to tell when to stop resending
 - Cannot achieve correctness without feedback

Forms of Feedback

- ACK: Yes, I got a packet
- NACK: No, I did not get the packet
- When is NACK a natural idea?
 - Packet Corruption (I got packet#5 but it was corrupted)
- Ignore NACKs for rest of the lecture...

Solution v2

- Resend packet until you get an ACK
 - And receiver sends per-packet ACKs until data finally stops
- Correct?
 - Yes:
 - All dropped/corrupted packets will be retransmitted
 - The transport will attempt to make progress
- Fair?
 - Over long-term, yes:
 - all sources will get an equal chance to use network resources
- Flow performance?
 - Good but not necessarily optimal
 - Unnecessarily retransmitted packets may inflate latency
- Utilization:
 - suboptimal; packets retransmitted unnecessarily

Solution v3

- Send packet
 - But now, **set a timer**
- When receiver gets packet, sends ACK
- If sender receives ACK, done
- If no ACK when timer expires, resend
 - Still **correct**, and **fair**
 - **Performance** would argue for **small timeout**
 - **Utilization** would argue for **larger timeout**
 - May want to increase timer each time you try
 - May want to cap the number of retries
 - Problems with this design?

Have “Solved” the Single Packet Case

- Send packet
 - Set a timer
- If no ACK when timer goes off, resend packet
 - And reset timer
- Tradeoff between performance and utilization in selection of timeout:
 - Too small: unnecessary retransmissions (underutilization)
 - Too large: waiting unnecessarily (poor performance)

Multiple Packets

- Service model: reliable stream of packets
 - Hand up contiguous block of packets to application
- Why not use single-packet solution?
 - Send the next packet once the first one has been delivered
 - Problem: Only one packet “in flight” at a time
 - **Low Effective throughput: Packet Size / RTT**
- Use window based approach
 - Allow for a window of W packets in-flight at any time (unack'ed)
 - Slide the window as packets are ack'ed
 - Sliding window implies W packets are continuous

Window-based Algorithms

- Very simple concept
 - Send W packets
 - When one gets ACK'ed send the next packet in line
 - It really is that simple (until we got to TCP)
- Will consider several variations...
 - But first...

How Big Should the Window be?

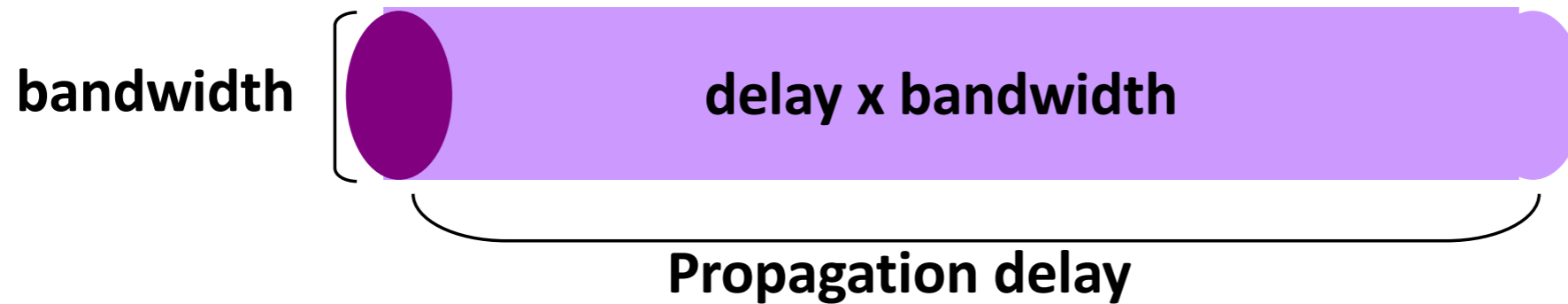
- **Windows serve three purposes**
 - Taking advantage of the bandwidth of the links
 - Limiting bandwidth used by a flow (congestion control)
 - Limiting the amount of buffering needed at the receiver
 - Why do receivers need to buffer packets?
 - Answer: packet re-ordering (discussed later)
- If we ignore all but the first goal, then we want to keep the sender always sending (in the ideal case)
 - RTT: from sending first packet until received first ACK
- **Condition:**
 - $RTT \times B \sim W \times \text{Packet Size}$

What does this mean?

- B is the minimum link bandwidth along the path
 - Obviously shouldn't send faster than that
- **We want to set W such that:**
 - if I am sending at rate B, then
 - the ACK of the first packet arrives
 - exactly when I just finish sending the last of my W packets
- **Lets me send as fast as the path can deliver...**

$RTT \times B \sim W \times \text{Packet Size}$

- Recall that **Bandwidth Delay Product**
 - $BDP = \text{bandwidth} \times \text{propagation delay}$



- **$B \times RTT$ is merely $2 \times BDP$**
- Window sizing rule:
 - Total bits in flight is roughly the amount of data that fits into forward and reverse “pipes”
 - Here pipe is complete path, not single link...
 - **This is not “detail”, this is a fundamental concept...**

Where Are We?

- **Figured out correctness condition:**
 - Always resend lost/corrupted packets
 - Always try to make progress (but can give up entirely)
- **Figured out single packet case:**
 - Send packet, set timer, resend if no ACK when timer expires
- **Some progress towards multiple packet case:**
 - Allow many packets (W) in flight at once
 - And know what the ideal window size is
 - $RTT \times B / \text{Packet size}$
- What's left to design?

Three Design Considerations

- Nature of feedback
 - What should ACKs tell us when we have many packets in flight
- Detection of loss
- Response to loss

ACK Individual Packets

- **Nature of feedback:** simple - the receiver ACKs each packet
- **Response to loss: moderate:**
 - + Retransmit the packet for which ACK not received
 - + Reordering not a problem
 - + Simple window algorithm
 - W independent single packet algorithms
 - When one finishes grab next packet
 - - **Loss of ACK packet requires a retransmission**

Full Information Feedback

- **List all packets that have been received**
 - Give highest cumulative ACK plus any additional packets
 - If packets 1, 2, 3, 4, 6 received: send ACK(4, 6)
- Strengths?
 - As much information as you could hope for
 - Resilient form of individual ACKs
- Weaknesses?
 - Could require sizable overhead in bad cases
 - Feasible if only small holes
 - If packets 1, 2, 3, 4, 6, ..., 100 received: ACK(4, 6,...,100)

Full Information Feedback

- **Nature of feedback: complex** - feedback may have high overheads
 - If packets 1, 2, 3, 4, 6,, 100 received: ACK(4, 6, ...,100)
- **Response to loss: simple:**
 - + Retransmit the packet for which ACK not received
 - + Reordering not a problem
 - + Simple window algorithm
 - - **Loss of ACK does not necessarily requires a retransmission**
 - **The next ACK will tell that the packet was indeed received**
 - Resilient form of individual ACKs

Cumulative ACK

- **Individual ACKs** can get lost, and require **unnecessary retransmission**
- **Full information feedback** can handle lost ACKs but has **high overheads**
- **Cumulative ACKs: a sweet spot between the two**
- Just the first part of full information feedback
- ACK the highest sequence number for all previously received packets
 - Implementations often send back “next expected packet”, but that’s just a detail

Cumulative ACKs (same example; say packet 5 lost)

Full information feedback:

- Stream of ACKs will be
 - Up to 1
 - Up to 2
 - Up to 3
 - Up to 4
 - Up to 4, plus 6
 - Up to 4, plus 6,7
 - Up to 4, plus 6,7,8
 - ...

Tells “**which**” packet arrived, and **which** packet did not

Cumulative ACKs:

- Stream of ACKs will be
 - Up to 1
 - Up to 2
 - Up to 3
 - Up to 4
 - Up to 4
 - Up to 4
 - Up to 4
 - ...

Tells “**some**” packet arrived, and **which** packet did not

Cumulative ACK

- **Individual ACKs** can get lost, and require **unnecessary retransmission**
- **Full information feedback** can handle lost ACKs but has **high overheads**
- **Cumulative ACKs: a sweet spot between the two**
- Just the first part of full information feedback
- ACK the highest sequence number for all previously received packets
 - Implementations often send back “next expected packet”, but that’s just a detail
- Strengths?
 - Resilient to lost ACKs
- Weaknesses?
 - Confused by reordering
 - Incomplete information about which packets have arrived

Detecting Loss

- If packet times out, assume it is lost...
- How else can you detect loss?

Loss With Individual ACKs

- Assume that packet 5 is lost, but no others
- Stream of ACKs will be
 - 1
 - 2
 - 3
 - 4
 - 6
 - 7
 - 8
 - ...

Loss With Individual ACKs

- Could resend packet when k “subsequent packets” are received
- Response to loss
 - Resend missing packet
 - Continue window based protocol

Loss With Full Information

- Same story, except that the “hole” is explicit in each ACK
- Stream of ACKs will be
 - Up to 1
 - Up to 2
 - Up to 3
 - Up to 4
 - Up to 4, plus 6
 - Up to 4, plus 6,7
 - Up to 4, plus 6,7,8
 - ...

Loss With Full Information

- Could resend packet when k “subsequent packets” are received
- Response to loss
 - Resend missing packet
 - Continue window-based protocol

Loss With Cumulative ACKs

- Assume packet 5 is lost, but no others
- Stream of ACKs will be
 - 1
 - 2
 - 3
 - 4
 - 4 (Sent when packet 6 arrives)
 - 4 (Sent when packet 7 arrives)
 - 4 (Sent when packet 8 arrives)
 - ...

Loss With Cumulative ACKs (cont'd)

- Duplicate ACKs are a sign of loss
 - The lack of ACK progress means 5 hasn't been delivered
 - Stream of duplicate ACKs means some packets are being delivered (one for each subsequent packet)
- Response to loss is trickier... When shall the source retransmit packet 5?
 - Packet may be delayed (so, source should wait)
 - Packet may be reordered (so, source should wait)
 - Or, packet may be dropped (source should immediately retransmit)
 - Impossible to know which one is the case
 - Life lesson: **be optimistic!**
 - Until optimism starts hurting
 - **Solution: retransmit after k duplicate ACKs**
 - **for some value of k, depending on how optimistic you feel!**

Cumulative ACKs (how is reordering handled; large k)

Receiver events:

- Packet 1 received
- Packet 2 received
- Packet 3 received
- Packet 4 received
- **Packet 6 received**
- Packet 7 received
- **Packet 5 received**
- **Packet 8 received**
- ...

Cumulative ACKs:

- Up to 1
- Up to 2
- Up to 3
- Up to 4
- **Up to 4**
- Up to 4
- **Up to 7**
- **Up to 8**
- ...

**Cumulative ACKs naturally handle packet reordering
(Packet delays are similar to reordering)**

Loss With Cumulative ACKs (cont'd 2)

- Two choices
 - Send missing packet and optimistically assume that subsequent packets have arrived
 - i.e., increase W by the number of duplicate ACKs
 - Send missing packet, wait for ACK
- Timeout-detected losses also problematic
 - If packet 5 times out, packet 6 is about to timeout also
 - Do you resend both?
 - Do you resend 5 and wait?
 - ...

Cumulative ACKs (confusion with duplication)

- Produce duplicate ACKs
 - Could be confused for loss with cumulative ACKs
 - But duplication is rare...

Source events:

- Packet 1 sent
- Packet 2 sent
- Packet 3 sent
- Packet 4 sent
- Packet 5 sent
- Packet 6 sent
- **Packet 3 resent**
- Packet 7 sent
- ...

Receiver events:

- Packet 1 received
- Packet 2 received
- -
- **Packet 4 received**
- Packet 5 received
- Packet 6 received
- **Packet 3 received**
- **Packet 3 received**
- Packet 7 received
- ...

Cumulative ACKs:

- Up to 1
- Up to 2
- -
- **Up to 2**
- **Up to 2**
- **Up to 2**
- Up to 6
- **Up to 6**
- **Up to 7**
- ...

Cumulative ACKs

- They make no sense, except as a cheap alternative to full information
 - Less state than full information
 - More resilient than individual ACKs
- But ambiguity in feedback leads to many problems
 - Have other packets arrived?
- Makes retransmission and congestion window management hard
- Will deal with these issues when we come to TCP

All The Bad Things Best Effort Can Do

- Packets can be lost
- Packets can be corrupted
- Packets can be **reordered**
- Packets can be **delayed**
- Packets can be **duplicated**

Effect of Reordering?

- For all designs this looks like “subsequent ACKs”
- This can be mistaken for packet loss
- Hard to realize the difference between these packet arrival patterns:
 - 1, 2, 3, 4, 6, 7, 8, 9,...
 - 1, 2, 3, 4, 6, 7, 8, 9, 5, 10,...

Effect of Long Delays?

- Possible timeouts (for all designs)

Effect of Duplication

- Produce duplicate ACKs
 - Could be confused for loss with cumulative ACKs
 - But duplication is rare...

Possible Design For Reliable Transport

- Full information ACKs
- Window based, with retransmissions after
 - Timeout
 - K subsequent ACKs
- This is correct, high-performant and high-utilization
- How about fairness?

Fairness? (Come back to later)

- Adjust W based on losses...
- In a way that flows receive same shares
- Short version:
 - Loss: cut W by 2
 - Successful receipt of window: W increased by 1

Overview of Reliable Transport

- Window based self control separate concerns
 - Size of W
 - Nature of feedback
 - Response to loss
- Can design each aspect relatively independently
- Can be correct, fair, high-performant and high-utilization

Many Implementation Choices

- Feedback from receiver: ACKs vs NACKs
 - Can NACKs alone achieve correctness
 - Can ACKs alone achieve correctness
- Variations on ACKs
 - Full information
 - Individual packets
 - Cumulative (TCP)
- When to resend
 - Timeout
 - Duplicate ACKs
 - NACKs

Implementation Choices

- These implementation choices affect:
 - Performance
 - Utilization
 - Fairness
 - ..
- These are important concerns
 - **But correctness is more fundamental**
- Design **must** start with correctness
 - Can then “engineer” its performance with various hacks
 - These hacks can be “fun”, but don’t let them distract you

What Have We Done so far?

- Started from first principles
 - Correctness condition for reliable transport
- ... to understanding **why feedback from receiver is necessary** (sol-v1)
- ... to understanding **why timers may be needed** (sol-v2)
- ... to understanding **why window-based design may be needed** (sol-v3)
- ... to radically **different many possible design choices**
 - Some of them close to modern TCP
- **You are now ready to learn TCP**

We tried to understand:

Why is TCP designed the way it is designed!

Why is almost always the most important question!!!