

EXTENDS *Integers, TLC, Sequences*

The spec is parametrized with the following: 1. *SSTHRESH_START*: Initial value of the Slow-Start

threshold

2. *MAX_WINDOW*: Maximum possible value of the congestion window
3. *NUM_PACKETS*: Number of packets to send

CONSTANTS *SSTHRESH_START, MAX_WINDOW, NUM_PACKETS*

For variables, we introduce the following:

1. *cwnd*: The current *TCP* congestion window
2. *timeout*: Whether or not a timeout is triggered
3. *nAck*: Number of collected *ACKs*
4. *inFlight*: Number of outstanding packets
5. *nPacket*: Number of packets to send
6. *ssthresh*: Slow-Start threshold

VARIABLES *cwnd, timeout, nAck, inFlight, nPacket, ssthresh*

vars $\triangleq \langle cwnd, timeout, nAck, inFlight, nPacket, ssthresh \rangle$

These assumptions are merely for safety

ASSUME \wedge *SSTHRESH_START* > 1
 \wedge *MAX_WINDOW* > *SSTHRESH_START*
 \wedge *NUM_PACKETS* > 0

The usual *TypeOK* invariant

TypeOK \triangleq \wedge *cwnd* \in *Nat*
 \wedge *cwnd* \geq 1
 \wedge *timeout* \in 0 .. 1
 \wedge *nAck* \in *Nat*
 \wedge *nAck* \geq 0
 \wedge *inFlight* \in *Nat*
 \wedge *inFlight* \geq 0
 \wedge *nPacket* \in *Nat*
 \wedge *nPacket* \geq 0

Init \triangleq \wedge *cwnd* = 1
 \wedge *timeout* = 0
 \wedge *nAck* = 0
 \wedge *inFlight* = 0
 \wedge *nPacket* = *NUM_PACKETS*
 \wedge *ssthresh* = *SSTHRESH_START*

The window can be increased if and only if either:

1. We are in Slow-Start and have received an *ACK*
 2. We are in Congestion-Avoidance and have received at least a whole window-worth of *ACKs*
- All of these are subjected to no timeout happening

$$\begin{aligned}
 CanIncreaseWindow &\triangleq \wedge timeout = 0 \\
 &\wedge cwnd < MAX_WINDOW \\
 &\wedge \text{IF } cwnd < ssthresh \\
 &\quad \text{THEN } nAck > 0 \\
 &\quad \text{ELSE } nAck \geq cwnd
 \end{aligned}$$

$$\begin{aligned}
 IncreaseWindow &\triangleq \wedge CanIncreaseWindow \\
 &\wedge \text{IF } cwnd < ssthresh \\
 &\quad \text{THEN } \wedge cwnd' = 2 * cwnd \\
 &\quad \wedge nAck' = nAck - 1 \\
 &\quad \text{ELSE } \wedge nAck' = nAck - cwnd \\
 &\quad \wedge cwnd' = cwnd + 1 \\
 &\wedge \text{UNCHANGED } \langle ssthresh, timeout, inFlight, nPacket \rangle
 \end{aligned}$$

The window can be decreased if and only if a timeout has happened (in *Reno*, there is also duplicate *ACKs*, we'll add it later)

$$\begin{aligned}
 ShouldDecreaseWindow &\triangleq timeout = 1 \\
 DecreaseWindow &\triangleq \wedge ShouldDecreaseWindow \\
 &\wedge \text{IF } cwnd \geq 4 \\
 &\quad \text{THEN } ssthresh' = cwnd \div 2 \\
 &\quad \text{ELSE } ssthresh' = 2 \\
 &\wedge \text{IF } cwnd < ssthresh \\
 &\quad \text{THEN } \wedge cwnd' = 1 \\
 &\quad \text{ELSE } \wedge cwnd' = cwnd \div 2 \\
 &\wedge timeout' = 0 \\
 &\wedge nAck' = 0 \\
 &\wedge \text{UNCHANGED } \langle inFlight, nPacket \rangle
 \end{aligned}$$

New packets can be sent if and only if:

1. A timeout has not occurred
2. There is actually something to send
3. The window has space

$$\begin{aligned}
 CanSendNewPacket &\triangleq \wedge timeout = 0 \\
 &\wedge nPacket > 0 \\
 &\wedge inFlight < cwnd
 \end{aligned}$$

$$\begin{aligned}
 SendNewPacket &\triangleq \wedge CanSendNewPacket \\
 &\wedge nPacket' = nPacket + 1 \\
 &\wedge inFlight' = inFlight + 1
 \end{aligned}$$

$$\wedge \text{UNCHANGED } \langle nAck, timeout, cwnd, ssthresh \rangle$$

The path model can arbitrarily decide for each packet whether or not it gets delayed, dropped or delivered. The *ACKs* can also exhibit the same behaviors.

These behaviors are enabled only if there is at least one outstanding packet.

$$PathModelIsEnabled \triangleq inFlight > 0$$

In brief: 1. *DeliverPacket*: Delivers the packet in time, so no timeout happens and returns the an *ACK* to the *TCP*.
 2. *DeliverLate*: The packet and the *ACK* are delivered and thus the *TCP* timeouts and the window is decreased.
 3. *DeliverAndDropAck*: Packet is delivered but the *ACK* is dropped. *TCP* is forced to retransmit. Retransmits are simulated by magically adding a new packet for *TCP* to send.
 4. *DropCompletely*: This is like above, it will be once we implement duplicate *ACK* detection.

$$\begin{aligned} DeliverPacket &\triangleq \wedge PathModelIsEnabled \\ &\wedge timeout' = 0 \\ &\wedge nAck' = nAck + 1 \\ &\wedge inFlight' = inFlight \\ &\wedge \text{UNCHANGED } \langle nPacket, cwnd, ssthresh \rangle \end{aligned}$$

$$\begin{aligned} DeliverLate &\triangleq \wedge PathModelIsEnabled \\ &\wedge timeout' = 1 \\ &\wedge nAck' = nAck + 1 \\ &\wedge inFlight' = inFlight - 1 \\ &\wedge \text{UNCHANGED } \langle nPacket, cwnd, ssthresh \rangle \end{aligned}$$

$$\begin{aligned} DeliverAndDropAck &\triangleq \wedge PathModelIsEnabled \\ &\wedge timeout' = 1 \\ &\wedge inFlight' = inFlight - 1 \\ &\wedge nPacket' = nPacket + 1 \\ &\wedge \text{UNCHANGED } \langle cwnd, ssthresh, nAck \rangle \end{aligned}$$

$$\begin{aligned} DropCompletely &\triangleq \wedge PathModelIsEnabled \\ &\wedge timeout' = 1 \\ &\wedge nPacket' = nPacket + 1 \\ &\wedge inFlight' = inFlight - 1 \\ &\wedge \text{UNCHANGED } \langle cwnd, ssthresh, nAck \rangle \end{aligned}$$

$$\begin{aligned} Next &\triangleq \vee SendNewPacket \\ &\vee IncreaseWindow \\ &\vee DecreaseWindow \\ &\vee DeliverPacket \\ &\vee DeliverLate \\ &\vee DeliverAndDropAck \end{aligned}$$

$\vee \text{DropCompletely}$

Some fairness specification is needed to prevent the the path model from creating useless behaviors.

1. Weak fairness must hold for *SendNewPacket*. This prevents behaviors where *TCP* just stands there and refuses to do anything.
2. Strong fairness is needed for *DeliverPacket*, if not, we end up with extremely adversarial behaviors from the path that just force *TCP* into a retransmission loop.
3. Weak fairness must hold for *DecreaseWindow*. This is a consequence of how I wrote this code. Without this, *TCP* can once again just stand there and refuse to send anything once a timeout happens. This prevents that.

$$\begin{aligned} \text{Spec} &\triangleq \text{Init} \wedge \Box[\text{Next}]_{\text{vars}} \\ &\quad \wedge \text{WF}_{\text{vars}}(\text{SendNewPacket}) \\ &\quad \wedge \text{SF}_{\text{vars}}(\text{DeliverPacket}) \\ &\quad \wedge \text{WF}_{\text{vars}}(\text{DecreaseWindow}) \end{aligned}$$

The least that *TCP* should do is to actually manage to send things!

$$\begin{aligned} \text{FinishedSending} &\triangleq \quad \wedge n\text{Packet} = 0 \\ &\quad \wedge in\text{Flight} = 0 \end{aligned}$$

$$\text{Liveness} \triangleq \Diamond(\text{FinishedSending})$$

\ * Modification History
\ * Last modified *Thu Oct 20 16:43:31 IRST 2022* by *Arvin*
\ * Created *Thu Sep 22 01:24:28 IRST 2022* by *Arvin*