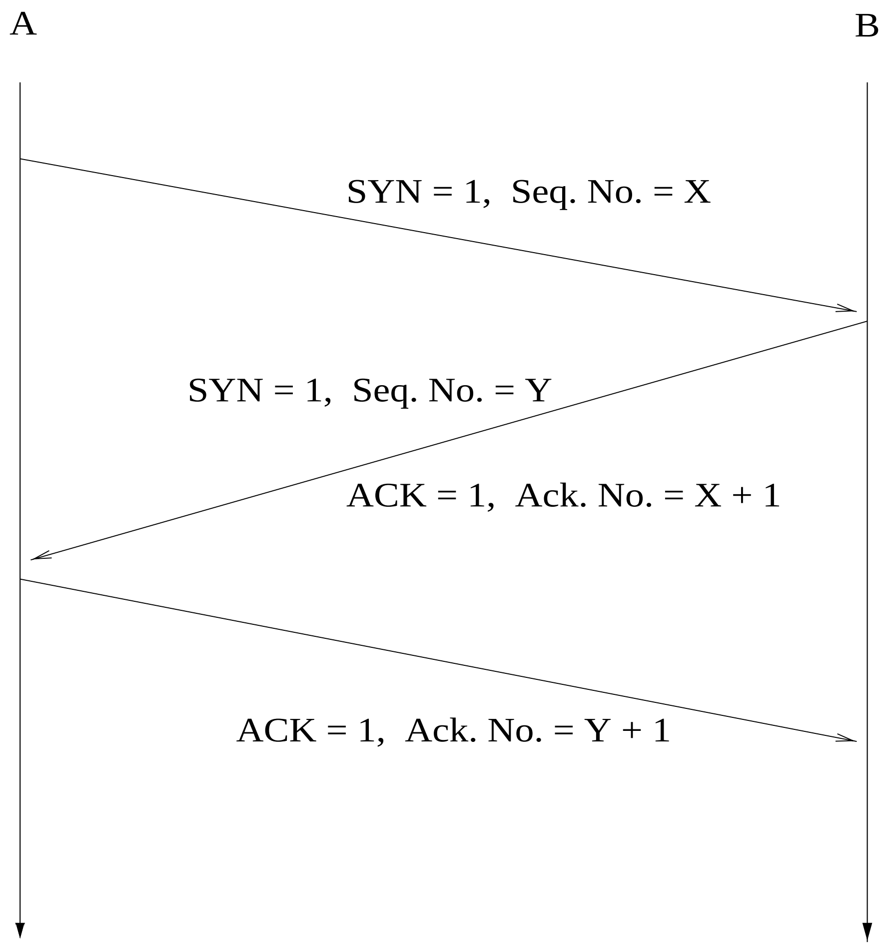
TCP connection establishment (3-way handshake):



- X, Y are chosen randomly

  $\longrightarrow$ sequence number prediction

- piggybacking

2-person consensus problem: are A and B in agreement about the state of affairs after 3-way handshake?

$\longrightarrow$ in general: impossible

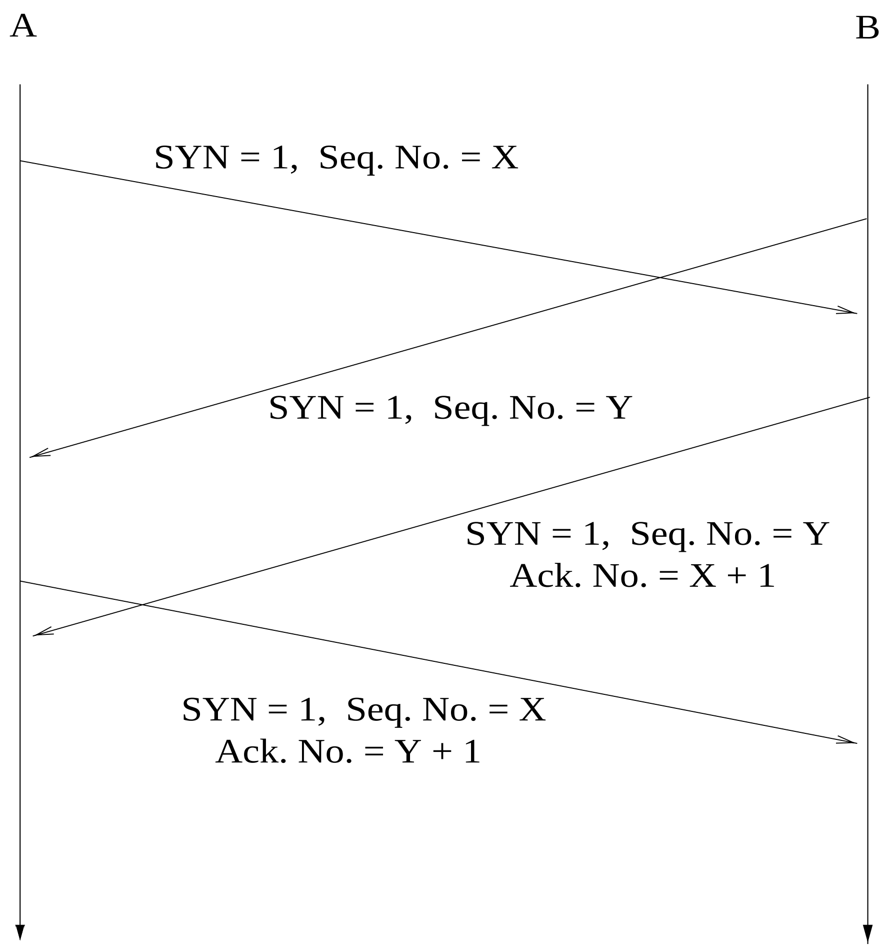
$\longrightarrow$ can be proven

$\longrightarrow$ "acknowledging the ACK problem"

$\longrightarrow$ also TCP session ending

$\longrightarrow$ lunch date problem

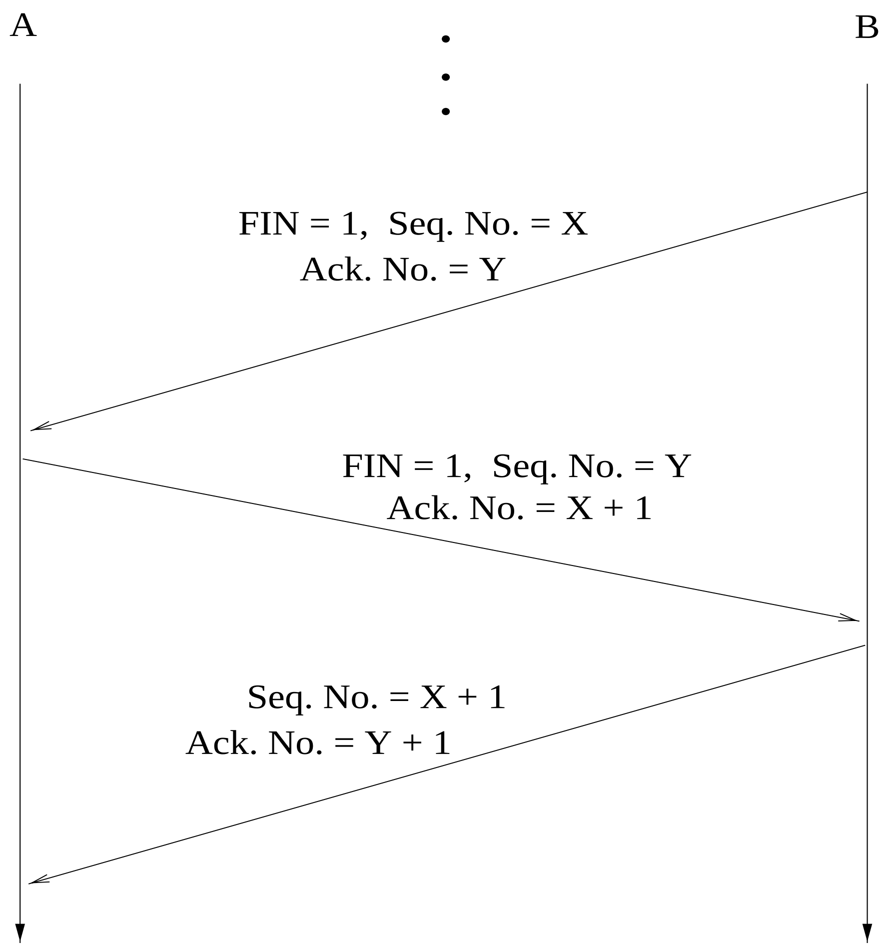
Call Collision:



$\longrightarrow$ only single TCB gets allocated

$\longrightarrow$ unique full association

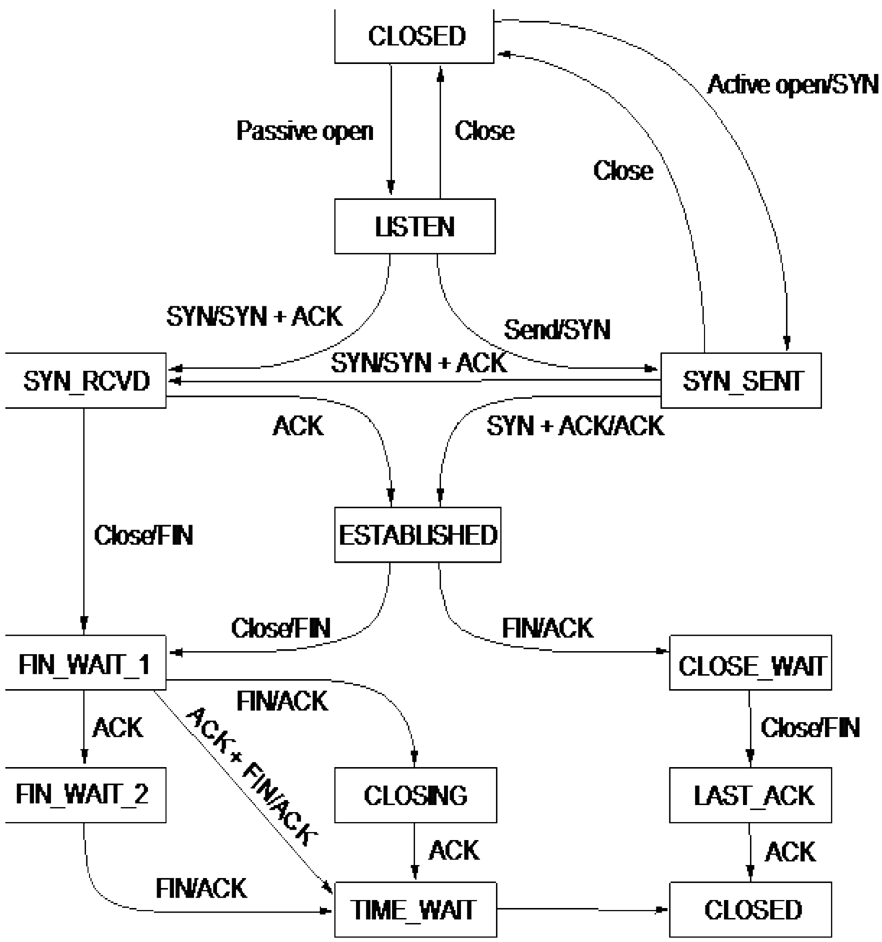
TCP connection termination:



- full duplex
- half duplex

More generally, finite state machine representation of TCP's control mechanism:

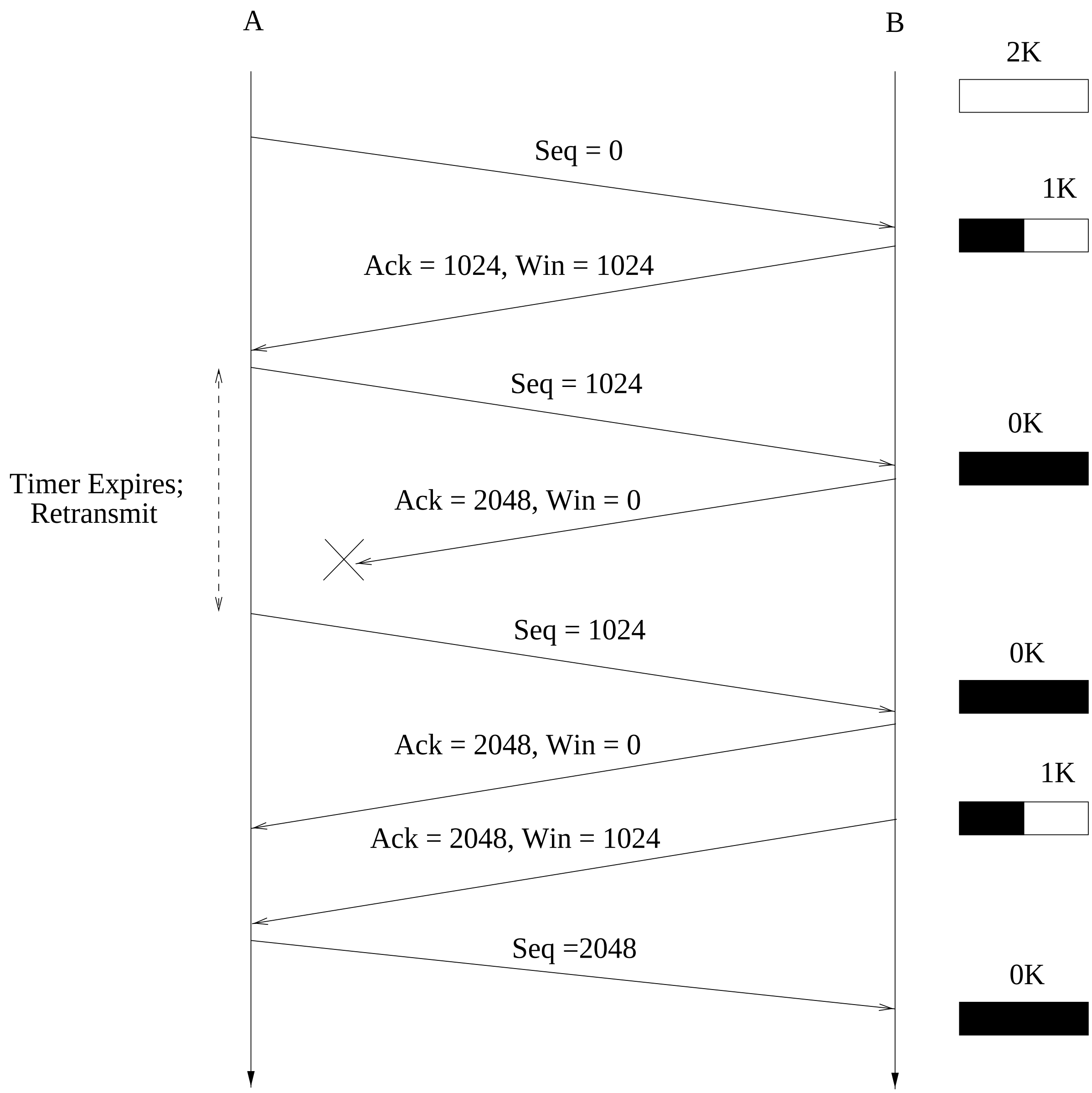
$\longrightarrow$ state transition diagram



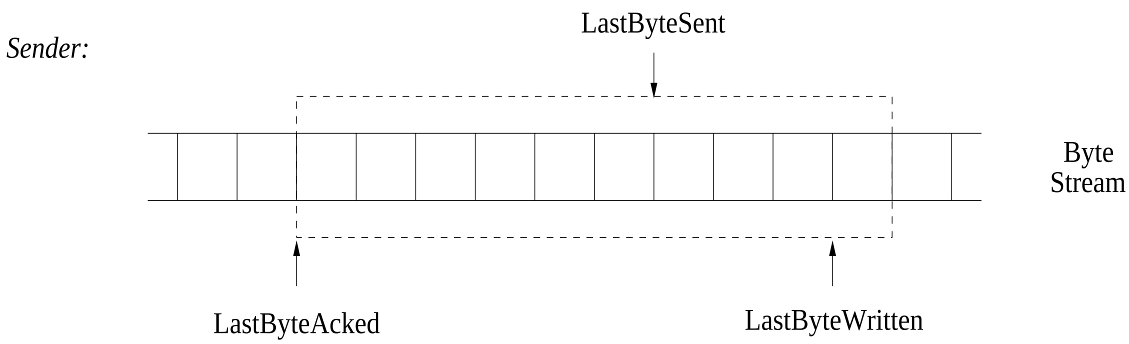
Features to notice:

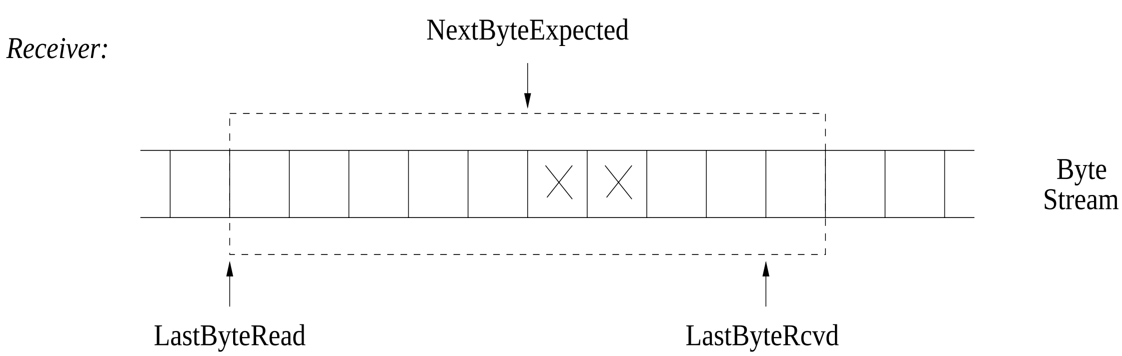
- Connection set-up:
  - client's transition to `ESTABLISHED` state without ACK
  - how is server to reach `ESTABLISHED` if client ACK is lost?
  - `ESTABLISHED` is macrostate (partial diagram)
- Connection tear-down:
  - three normal cases
  - special issue with `TIME WAIT` state
  - employs hack

Basic TCP data transfer:



TCP's sliding window protocol





- sender, receiver maintain buffers `MaxSendBuffer`, `MaxRcvBuffer`

Note asynchrony between TCP module and application.

Sender side: maintain invariants

- $\texttt{LastByteAcked} \leq \texttt{LastByteSent} \leq \texttt{LastByteWritten}$
- $\texttt{LastByteWritten}-\texttt{LastByteAcked} < \texttt{MaxSendBuffer}$

$\longrightarrow$ buffer flushing (advance window)

$\longrightarrow$ application blocking

- $\texttt{LastByteSent}-\texttt{LastByteAcked} \leq \texttt{AdvertisedWindow}$

Thus,

$$\texttt{EffectiveWindow} = \texttt{AdvertisedWindow} - (\texttt{LastByteSent} - \texttt{LastByteAcked})$$

$\longrightarrow$ upper bound on new send volume

Actually, one additional refinement:

$\longrightarrow$ `CongestionWindow`

`EffectiveWindow` update procedure:

$$\texttt{EffectiveWindow} = \texttt{MaxWindow} - (\texttt{LastByteSent} - \texttt{LastByteAcked})$$

where

$$\texttt{MaxWindow} = \min\{\,\texttt{AdvertisedWindow}, \texttt{CongestionWindow}\,\}$$

How to set `CongestionWindow`.

$\longrightarrow$ domain of TCP congestion control

Receiver side: maintain invariants

- $\texttt{LastByteRead} < \texttt{NextByteExpected} \leq \texttt{LastByteRcvd} + 1$
- $\texttt{LastByteRcvd} - \texttt{NextByteRead} < \texttt{MaxRcvBuffer}$

$\longrightarrow$ buffer flushing (advance window)

$\longrightarrow$ application blocking

Thus,

$$\texttt{AdvertisedWindow} = \texttt{MaxRcvBuffer} - (\texttt{LastByteRcvd} - \texttt{LastByteRead})$$

Issues:

How to let sender know of change in receiver window size after `AdvertisedWindow` becomes 0?

- trigger ACK event on receiver side when `AdvertisedWindow` becomes positive
- sender periodically sends 1-byte probing packet

$\longrightarrow$ design choice: smart sender/dumb receiver

$\longrightarrow$ same situation for congestion control

Silly window syndrome: Assuming receiver buffer is full, what if application reads one byte at a time with long pauses?

- can cause excessive 1-byte traffic
- if `AdvertisedWindow` $<$ MSS then set `AdvertisedWindow` $\leftarrow 0$

Do not want to send too many 1 B payload packets.

Nagle's algorithm:

- rule: connection can have only one such unacknowledged packet outstanding
- while waiting for ACK, incoming bytes are accumulated (i.e., buffered)

. . . compromise between real-time constraints and efficiency.

$\longrightarrow$ useful for `telnet`-type applications

Sequence number wrap-around problem: recall sufficient condition

$$\texttt{SenderWindowSize} < (\texttt{MaxSeqNum} + 1)/2$$

$\longrightarrow$ 32-bit sequence space/16-bit window space

However, more importantly, time until wrap-around important due to possibility of roaming packets.

bandwidth	time until wrap-around †
T1 (1.5 Mbps)	6.4 hrs
Ethernet (10 Mbps)	57 min
T3 (45 Mbps)	13 min
F/E (100 Mbps)	6 min
OC-3 (155 Mbps)	4 min
OC-12 (622 Mbps)	55 sec
OC-24 (1.2 Gbps)	28 sec

Even more importantly, "keeping-the-pipe-full" consideration.

bandwidth	delay-bandwidth product †
T1 (1.5 Mbps)	18 kB
Ethernet (10 Mbps)	122 kB
T3 (45 Mbps)	549 kB
FDDI (100 Mbps)	1.2 MB
OC-3 (155 Mbps)	1.8 MB
OC-12 (622 Mbps)	7.4 MB
OC-24 (1.2 Gbps)	14.8 MB

$\longrightarrow$ 100 ms latency

Also, throughput limitation imposed by TCP receiver window size.

$\longrightarrow$ e.g., high-performance grid apps

RTT estimation

... important to not underestimate nor overestimate.

Karn/Partridge: Maintain running average with precautions

$$\texttt{EstimateRTT} \leftarrow \alpha \cdot \texttt{EstimateRTT} + \beta \cdot \texttt{SampleRTT}$$

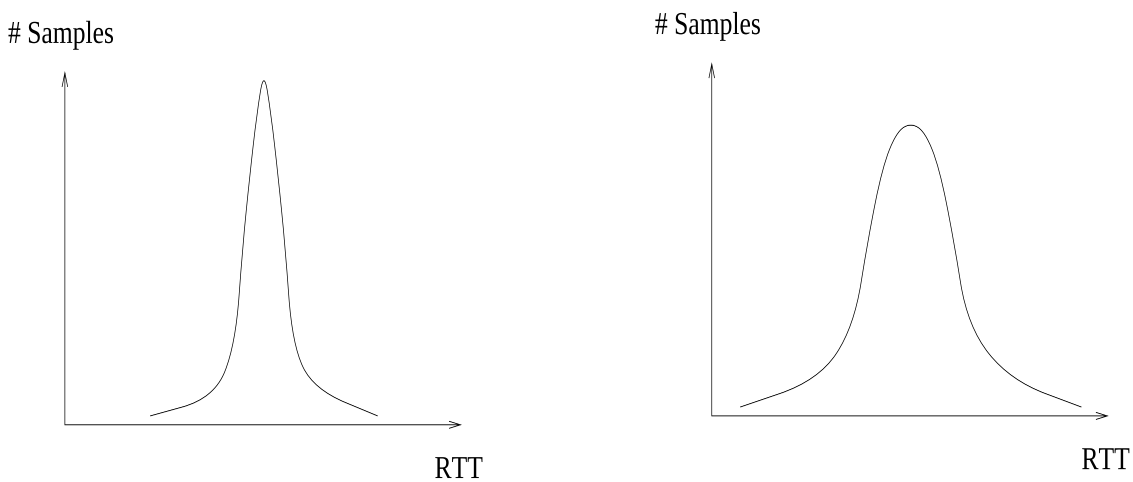
- `SampleRTT` computed by sender using timer
- $\alpha + \beta = 1$; $0.8 \leq \alpha \leq 0.9$, $0.1 \leq \beta \leq 0.2$
- $\texttt{TimeOut} \leftarrow 2 \cdot \texttt{EstimateRTT}$ or
  $\texttt{TimeOut} \leftarrow 2 \cdot \texttt{TimeOut}$ (if retransmit)

$\longrightarrow$ need to be careful when taking `SampleRTT`

$\longrightarrow$ infusion of complexity

$\longrightarrow$ still remaining problems

Hypothetical RTT distribution:



⟶ need to account for variance

⟶ not nearly as nice

Jacobson/Karels:

- $\texttt{Difference} = \texttt{SampleRTT} - \texttt{EstimatedRTT}$
- $\texttt{EstimatedRTT} = \texttt{EstimatedRTT} + \delta \cdot \texttt{Difference}$
- $\texttt{Deviation} = \texttt{Deviation} + \delta(|\texttt{Difference}| - \texttt{Deviation})$

Here $0 < \delta < 1$.

Finally,

- $\texttt{TimeOut} = \mu \cdot \texttt{EstimatedRTT} + \phi \cdot \texttt{Deviation}$

where $\mu = 1$, $\phi = 4$.

$\longrightarrow$ persistence timer

$\longrightarrow$ how to keep multiple timers in UNIX