CSE 232: Programming Assignment 4
Network simulation and TCP congestion control analysis using ns3

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November 2024

Question 1. Run the simulation with the default parameters (provided in the table) and answer the following questions.

a.) What is the maximum expected value (theoretical) of throughput (in Mbps)? Why?

The maximum throughput of the network is equivalent to the bottleneck bandwidth of the network. The bandwidth between the nodes `N0` and `N1` is 10 Mbps and the bandwidth between the nodes `N1` and `N2` is 7 Mbps. The bottleneck bandwidth will be the minimum of both these bandwidths. Hence, the maximum value of expected throughput is **7 Mbps**.

b.) How much is Bandwidth-Delay-Product (BDP)? Express your answer in terms of the number of packets.

We know that

$$\text{BDP} = \text{Bandwidth} \times \text{End-to-end delay}$$

Here, the bandwidth is equivalent to the bottleneck bandwidth (**7 Mbps** in this case) and end-to-end delay is the total round trip time for the packet between the nodes `N0` and `N2` through `N1` and the transmission delay between them.

$$\begin{aligned}
\text{End-to-end delay} &= \text{RTT between } N_0 \text{ and } N_2 + 2 \times d_{trans} \\
&= 2 \times (\text{delay between } N_0 \text{ and } N_2) + \frac{2 \times 1460 \times 8}{7 \times 10^6} \\
&= 2 \times (\text{delay between } N_0 \text{ and } N_1 + \text{delay between } N_1 \text{ and } N_2) \\
&= 2 \times (100 + 10) = 2 \times 110 \\
&= 223.33\,\text{ms}
\end{aligned}$$

Hence,

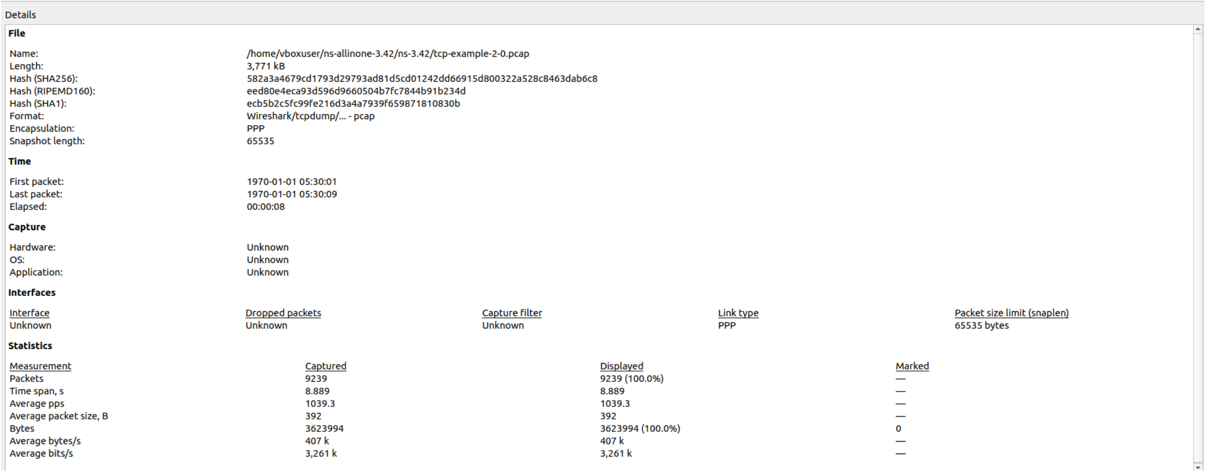
$$\begin{aligned}
\text{BDP} &= 7\text{Mbps} \times 223.33\text{ms} \\
&= 1563.31 \times 10^6 \times 10^{-3}\text{bytes} \\
&\approx 1.56\text{Mb}
\end{aligned}$$

Application Payload size = 1460 bytes = 11680 bits.

$$\begin{aligned}
\text{Number of packets} &= \frac{\text{BDP}}{\text{Payload size}} \\
&= \frac{1.56 \times 10^6}{11680} \approx 133\,\text{packets}
\end{aligned}$$

Hence, the BDP in terms of number of packets is **133 packets**.

c.) What is the average computed throughput of the TCP transfer?



Details

File

Name:	/home/vboxuser/ns-allinone-3.42/ns-3.42/tcp-example-2-0.pcap
Length:	3,771 kB
Hash (SHA256):	582a3a4679cd1793d29793ad81d5cd01242dd66915d800322a528c8463dab6c8
Hash (RIPEMD160):	eed80e4eca93d596d9660504b7fc7844b91b234d
Hash (SHA1):	ecb5b2c5fc99fe216d3a4a7939f659871810830b
Format:	Wireshark/tcpdump/... - pcap
Encapsulation:	PPP
Snapshot length:	65535

Time

First packet:	1970-01-01 05:30:01
Last packet:	1970-01-01 05:30:09
Elapsed:	00:00:08

Capture

Hardware:	Unknown
OS:	Unknown
Application:	Unknown

Interfaces

Interface	Dropped packets	Capture filter	Link type	Packet size limit (snaplen)
Unknown	Unknown	Unknown	PPP	65535 bytes

Statistics

Measurement	Captured	Displayed	Marked
Packets	9239	9239 (100.0%)	—
Time span, s	8.889	8.889	—
Average pps	1039.3	1039.3	—
Average packet size, B	392	392	—
Bytes	3623994	3623994 (100.0%)	0
Average bytes/s	407 k	407 k	—
Average bits/s	3,261 k	3,261 k	—

Figure 1: Received Packet

$$\text{Bytes sent} = 3623994$$

$$\text{Time taken} = 8.889\,\text{seconds}$$

$$\text{Throughput} = \frac{\text{Bytes sent}}{\text{Time taken}} = \frac{3623994 \times 8}{8.889 \times 10^6}$$

$$\approx 3.262\,\text{Mbps}$$

Hence, the average computed throughput of the TCP transfer is **3.262 Mbps**.

d.) Is the achieved throughput approximately equal to the maximum expected value? If it is not, explain the reason for the difference.

No, the achieved throughput (**3.262 Mbps**) is not equal to the maximum expected value (**7 Mbps**). The achieved throughput can be less than the expected throughput due to the following possible reasons:

- **Packet retransmissions:** The sender might have to retransmit packets due to lost ACKs or packets.
- **Network Congestion:** The size of the receiver buffer might not be large enough, hence leading to the dropping of packets due to overflowing buffers caused by network congestion.
- **End-to-end delay:** The end-to-end delay between receiver and sender could be one of the reasons leading to inefficient utilization of the bandwidth available.

e.) Plot Congestion Window (CWND) with time.

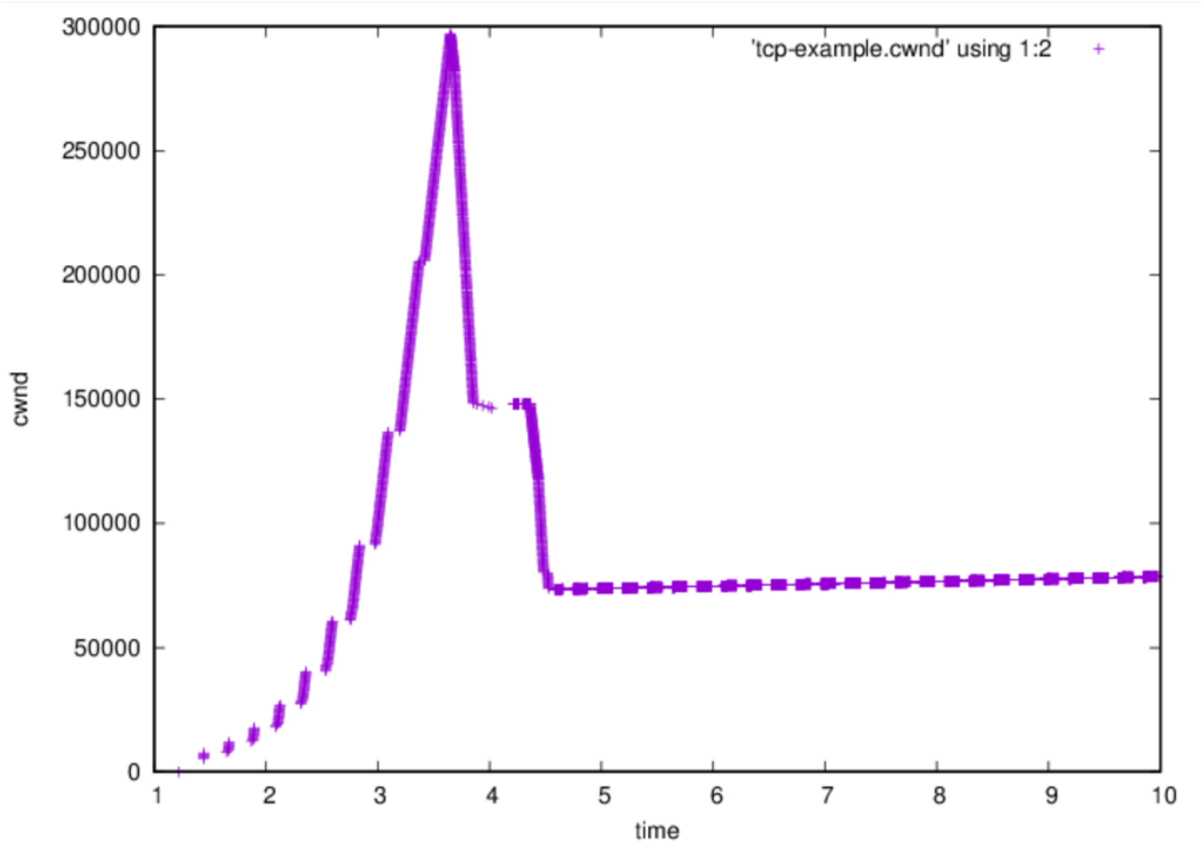


Figure 2: Congestion Window vs Time

f.) Plot queueing delay with time.

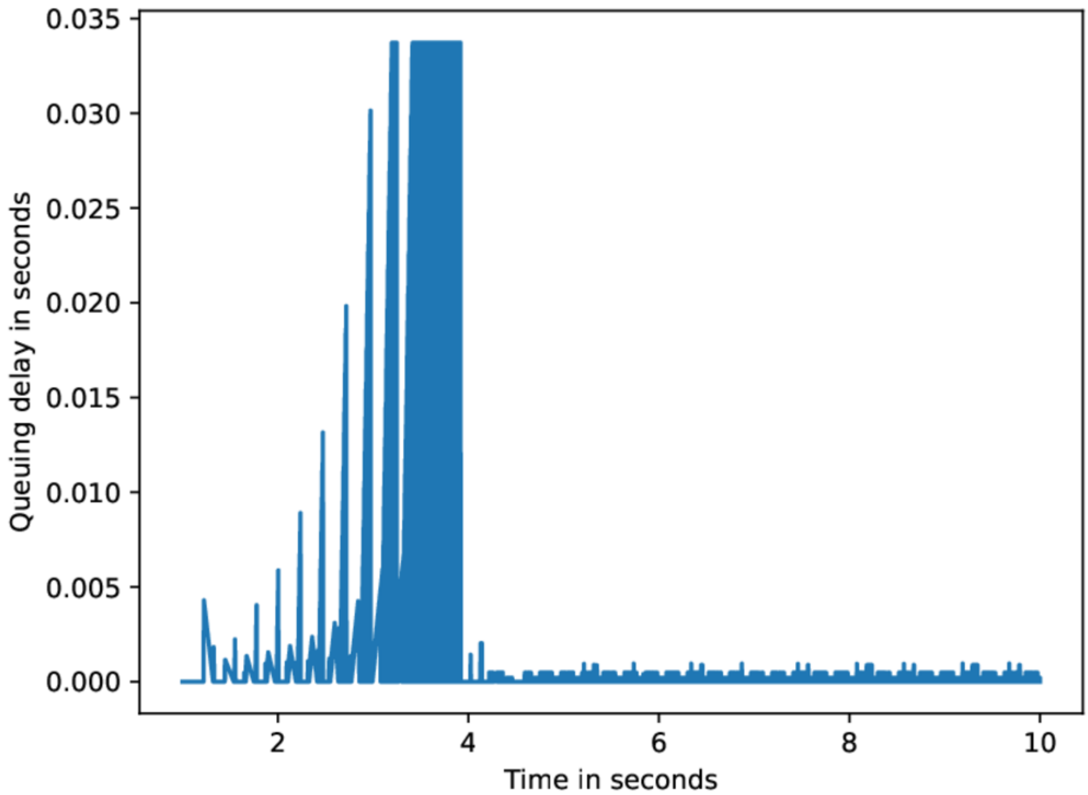


Figure 3: Queueing Delay vs Time

g.) Are the plots in 1(e) and 1(f) related?

Yes, the plots in **1(e)** and **1(f)** are related.
We notice that as the congestion window increases exponentially during the slow start phase, the queueing delay also increases correspondingly as more packets are being sent over the packet as the congestion window increases, leading to higher queueing delays.
As the congestion window drops around 4 seconds, likely due to a congestion event, the queueing delay also drops significantly, indicating that fewer packets are now being sent as congestion avoidance.
After the congestion is controlled, the network reaches a congestion avoidance phase where the congestion window is now stably increasing linearly with time. The queueing delay has also become stable, indicating reduced congestion.

Question 2. Change queue size to 1000.

a.) What is the average computed throughput of the TCP transfer?

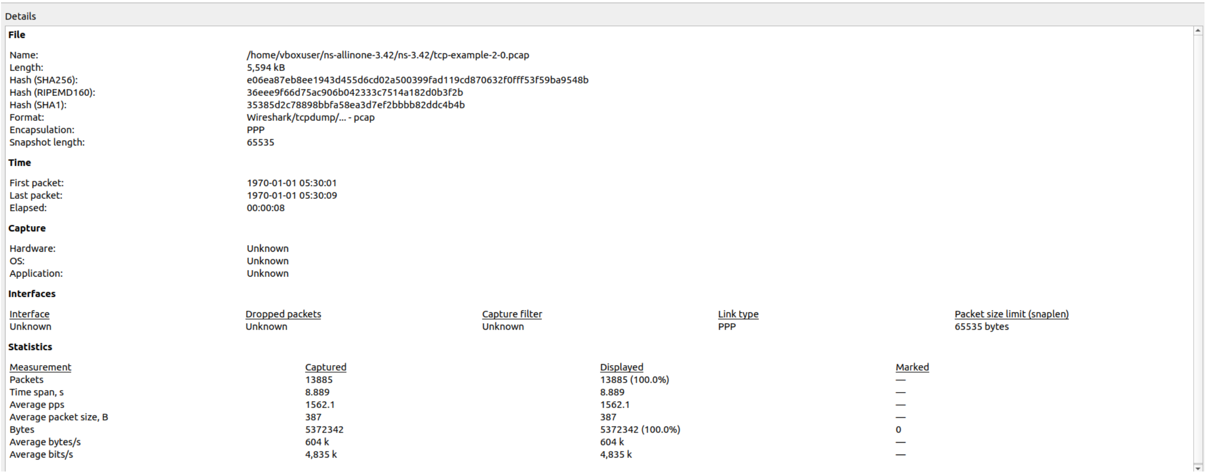


Figure 4: Received Packet

$$\text{Bytes sent} = 5372342$$

$$\text{Time taken} = 8.889\,\text{seconds}$$

$$\text{Throughput} = \frac{\text{Bytes sent}}{\text{Time taken}} = \frac{5372342 \times 8}{8.889 \times 10^6}$$

$$\approx 4.835\,\text{Mbps}$$

Hence, the average computed throughput of the TCP transfer is **4.835 Mbps**.

b.) Plot CWND with time.

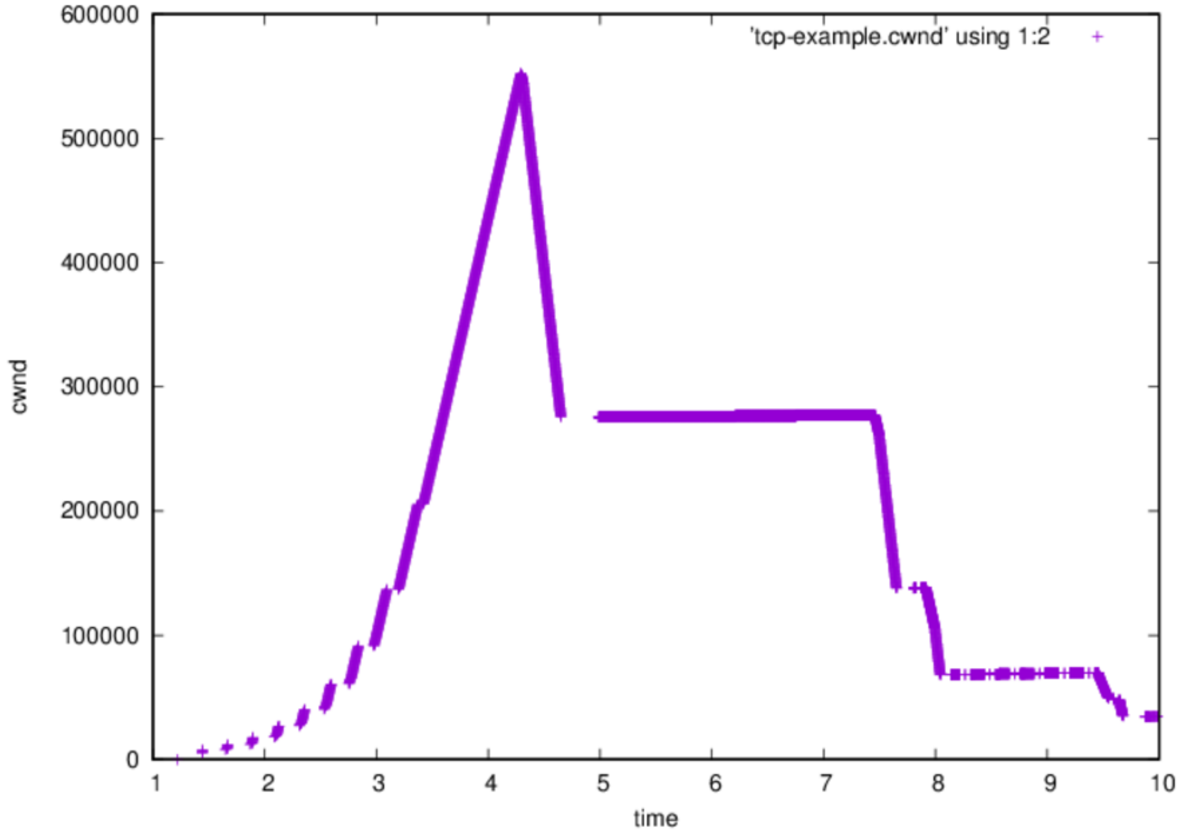


Figure 5: Congestion Window vs Time

c.) Plot queueing delay with time.

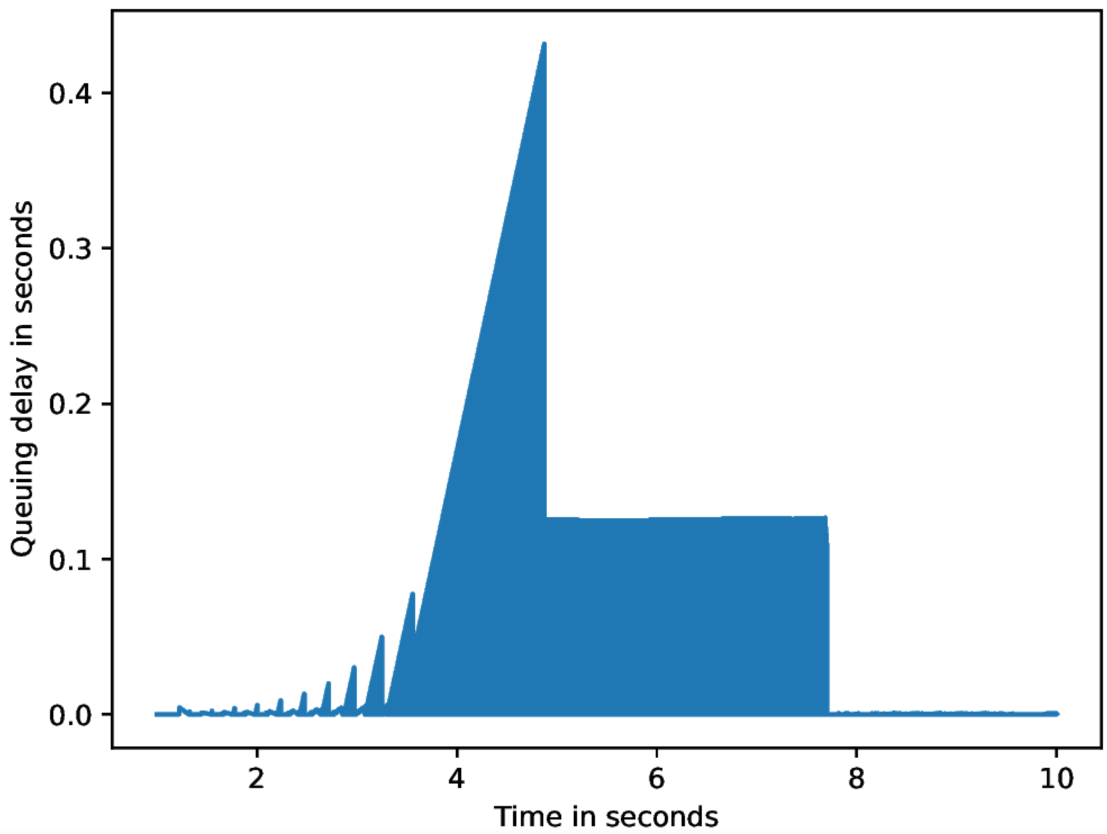


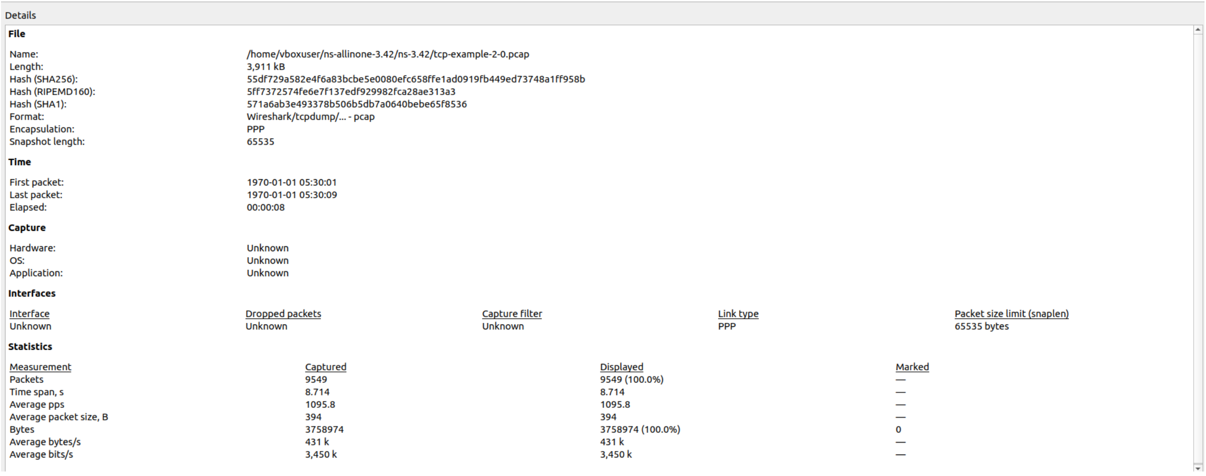
Figure 6: Queueing Delay vs Time

d.) Compare CWND plots of Q.1. and Q.2.; what insights did you gain?

From the CWND plots of Q1 and Q2, we notice that the congestion window of plot 2 increases for a longer time and reaches a higher peak than plot 1. This is due to increased queue size, which allows for a larger buffer, hence allowing the sender to send more packets over the network and the overflow does not happen quickly. Due to the higher congestion window, we notice more drops in size as compared to plot 1 during the congestion avoidance phase.

Question 3. Change N1-N2 bandwidth to 10 Mbps and N1-N2 delay to 100ms.

a.) What is the average computed throughput of the TCP transfer?



Details

File

Name:	/home/vboxuser/ns-allinone-3.42/ns-3.42/tcp-example-2-0.pcap
Length:	3,911 kB
Hash (SHA256):	55df729a582e4f6a83bcbe5e0080efc658ffe1ad0919fb449ed73748a1ff958b
Hash (RIPEMD160):	5ff7372574fe6e7f137edf929982fca28ae313a3
Hash (SHA1):	571a6ab3e493378b506b5db7a0640bebe65f8536
Format:	Wireshark/tcpdump/... - pcap
Encapsulation:	PPP
Snapshot length:	65535

Time

First packet:	1970-01-01 05:30:01
Last packet:	1970-01-01 05:30:09
Elapsed:	00:00:08

Capture

Hardware:	Unknown
OS:	Unknown
Application:	Unknown

Interfaces

Interface	Dropped packets	Capture filter	Link type	Packet size limit (snaplen)
Unknown	Unknown	Unknown	PPP	65535 bytes

Statistics

Measurement	Captured	Displayed	Marked
Packets	9549	9549 (100.0%)	—
Time span, s	8.714	8.714	—
Average pps	1095.8	1095.8	—
Average packet size, B	394	394	—
Bytes	3758974	3758974 (100.0%)	0
Average bytes/s	431 k	431 k	—
Average bits/s	3,450 k	3,450 k	—

Figure 7: Received Packet

$$
\begin{aligned}
\text{Bytes sent} &= 3758974 \\
\text{Time taken} &= 8.714\,\text{seconds} \\
\text{Throughput} &= \frac{\text{Bytes sent}}{\text{Time taken}} = \frac{3758974 \times 8}{8.714 \times 10^6} \\
&\approx 3.451\,\text{Mbps}
\end{aligned}
$$

Hence, the average computed throughput of the TCP transfer is **3.451 Mbps**.

b.) Plot CWND with time.

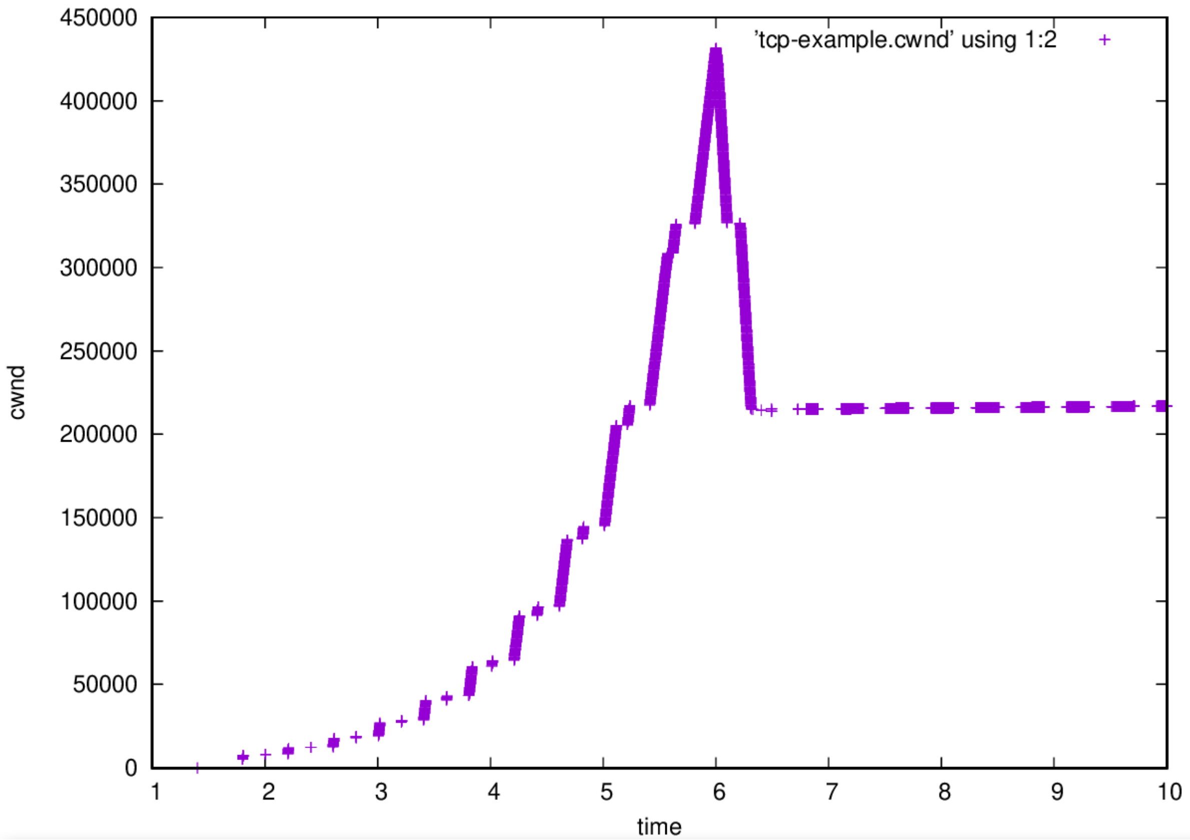


Figure 8: Congestion Delay vs Time

c.) Plot queueing delay with time.

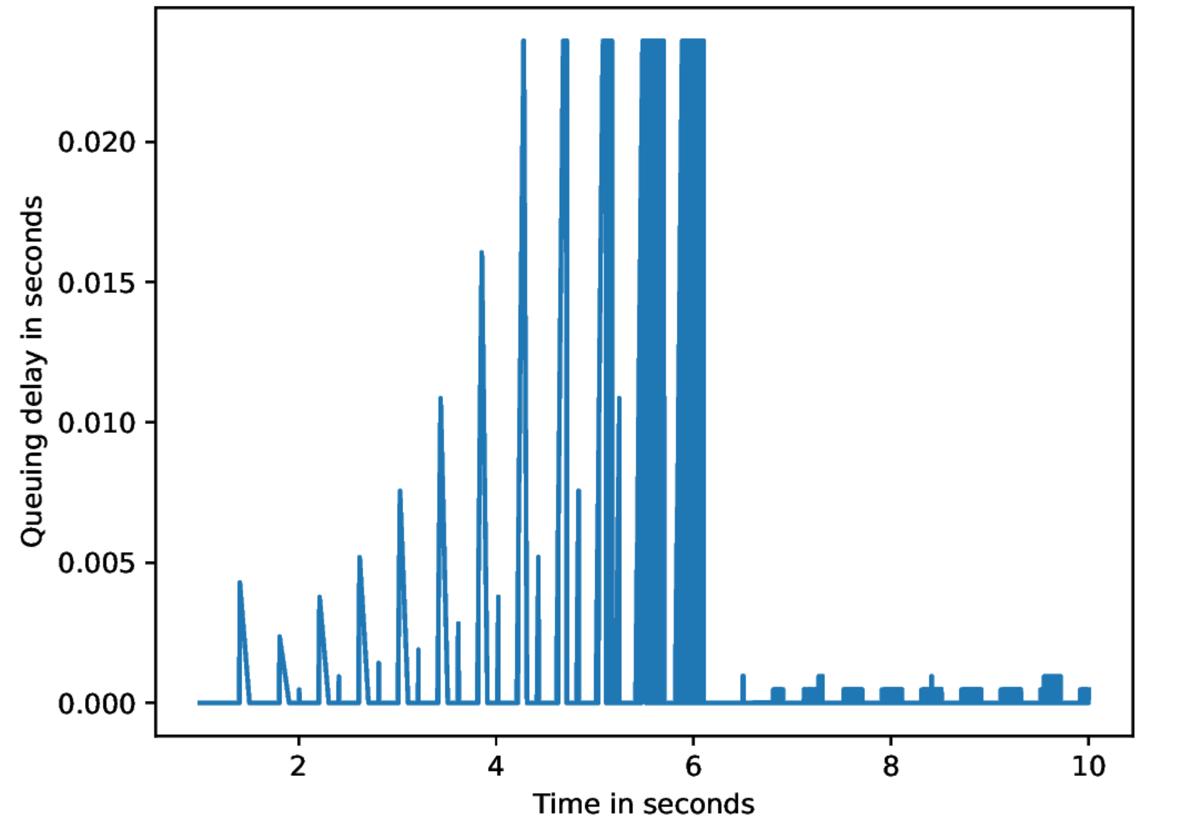


Figure 9: Queueing Delay vs Time

d.) Compare queuing delay plots of Q.1. and Q.3.; what insights did you gain?

By comparing queueing delay plots of Q1 and Q3, we gain the following insights:

- Since there is a mismatch in the bandwidth between the nodes in the first case, it leads to a buildup of the queue as the transmission rate of 7Mbps is slower than the arrival rate. Hence, the peak of queueing delay is higher in case 1 compared to case 2 and is reached comparatively faster.
- There is a delay mismatch between both the links in the first case so it further leads to queue buildup too. When the delay is similar in second case, it smoothens the queueing delay curve due to delayed ACKs and transmissions.

We can conclude that the enqueue time is higher in the first case as compared to dequeue time leading to higher delays.

References

[1] GitHub

[2] GeeksForGeeks: TCP Congestion Control

[3] NS3: TcpSocket Class Reference