Network Simulation

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1 Two Nodes

The first task of this project was to set up a very simple, two-hop network in the simulation and run three simulations using different parameters each time. This ensured that the simulation worked correctly and served to verify the measurements before performing longer and more complicated experiments. This simulated network consisted of two nodes, n1 and n2, connected with a bidirectional link.

1.1 Network Configuration

Each of the three tests required a slightly different configuration for the networks used. The three configurations were defined in separate files with the same general format:

```
# n1 -- n2
# network configuration
n1 n2
n2 n1

# link configuration
n1 n2 1Mbps 1000ms
n2 n1 1Mbps 1000ms
```

The first four lines define the general network structure and are the same for each network file The last three lines initialize the link parameters – bandwidth and propagation delay, respectively. The example shown was used in the first test. The other tests used the following configurations:

```
n1 n2 100bps 10ms
n2 n1 100bps 10ms
```

```
n1 n2 1Mbps 10ms
n2 n1 1Mbps 10ms
```

1.2 Testing Process

In the first two tests, a single 1 KB packet was sent from n1 to n2. For the second test, four packets were sent, each 1 KB in size. The first three were sent immediately, the fourth after a two second delay. An event handler was triggered upon the arrival of each packet in the three tests which output: 1) the packet identifier (a number assigned to each packet that indicated the order in which they were created), 2) the time at which the packets were created, and 3) the time at which the packets arrived at n2.

1.3 Results

Test	Packet ID	Creation Time (s)	Arrival Time (s)
1	1	0.000	1.008
2	1	0.000	80.01
3	1	0.000	0.018
	2	0.000	0.026
	3	0.000	0.034
	4	2.000	2.018

1.4 Analysis

The total delay for a packet is a combination of the transmisson delay, the queueing delay, and the propagation delay. Since the transmission delay is equivalent to L/R, where L is the size of the packet and R is the bandwidth, the equation for delay can be represented as:

$$d = L/R + d_{prop} + d_{queue}$$

where d_{prop} is the propagation delay and d_{queue} is the queueing delay In the case of the first test, $L = 1$ KB, $R = 1$ Mbps, $d_{prop} = 1$ s, and, since only one packet was sent, there was no queueing delay. This means that the total delay for the single packet sent in the first test should be

$$8000/1000000 + 1 = 1.008$$

The second test can be verified in the same way. The single packet is 1 KB, as in the first test. It uses a link with 100 bps bandwidth and a propagation delay of 10 ms, therefore, substituting these values gives the equation

$$8000/100 + .01 = 80.01$$

The calculations for the third test are a little complicated. It involved sending 4 packets, each 1 KB in size. The bandwidth of the link was 1 Mbps and the propagation delay was 10 ms. This yields a transmission delay of 8000/1000000, or .008 seconds. Since the first three were created at the same time, there was some queueing delay for the second and third packets, each staying in the queue until the previous packet was sent. The first packet had a delay of

$$.008 + .010 = .018$$

d_{queue} of the second packet is equivalent to d_{trans} of the first packet, or .008 seconds, which means the total delay for the packet was

$$.008 + .008 + .010 = .0026$$

The third packet was in the queue for 0.008 seconds longer than the second, since it could not transmit until the second packet had. The total delay for that packet is then $.0026 + .008$, or .034. The fourth packet was created after the first three packets had arrived, so it did not have to queue. The total delay of this packet is equal to the thrid packet, .018 seconds, and since it was created at 2 seconds, it arrived at 2.018 seconds.

2 Three Nodes

The second phase involved a more complicated network consisting of two hops, from n1 to n2, and from n2 to n3. As in the first part, there were three separate tests on three different configurations of this network structure.

2.1 Network Configuration

The network was configured in each file in and identical format, with n1 linked to n2 and n2 linked to n3. In both cases, the links were bidirectional. The first simulation's network was set up as follows:

```
# n1 -- n2 -- n3
# network configuration
n1 n2
n2 n1 n3
n3 n2

# link configuration
n1 n2 1Mbps 100ms
n2 n1 1Mbps 100ms
n2 n3 1Mbps 100ms
n3 n2 1Mbps 100ms
```

The second test case was very similar, the only difference was the bandwidth of the links was initialized to 1 Gbps instead of 1 Mbps. The third case used the same configuration for the links between n1 and n2, but the links between n2 and n3 had a bandwidth of 256 Kbps.

2.2 Testing Process

In the three tests of this phase, 1,000 packets, each 1 KB in size, were created and sent from n1 to n3, passing through n2. These packets were not queued at n1, since the transmission delay was calculated beforehand and each packet was created after the previous packet was transmitted, i.e. for $packet_n$, the creation time was $d_{trans} * (n-1)$. As in the first phase, after each packet arrived at the destination, its identifier, creation time, and arrival time were printed.

2.3 Results

The following table shows the output from the last 5 packets receieved in each test case. The arrival time of the last packet of each test represents how much time it requires to send a 1 MB file from n1 to n3 with the network used for that test.

Test	Packet ID	Creation Time (s)	Arrival Time (s)
1	997	7.968	8.184
	998	7.976	8.192
	999	7.984	8.200
	1000	7.992	8.208
	1001	8.000	8.216
2	997	0.007968	0.207984
	998	0.007976	0.207992
	999	0.007984	0.208000
	1000	0.007992	0.208008
	1001	0.008000	0.208016
3	997	7.968	31.36425
	998	7.976	31.39550
	999	7.984	31.42675
	1000	7.992	31.45800
	1001	8.000	31.48925

2.4 Analysis

The addition of a third node means that the total delay must also factor in the queuing, transmission, and propagation delays of the third node. In the first two tests, however, there is no queueing delay at n2. The links from n1 and n2 have the same bandwidth, meaning the transmission delay is the same for both. In the first test case, $L = 8000$ bits, and $R = 1000000$ bps, so $d_{trans} = .008$. With a propagation delay of .1 seconds, the first packet will arrive at n2 after .108 seconds. The second packet, created at .008 seconds, will arrive at n2 .008 seconds later, at .116 seconds. At the same time, the first packet will have finished transmitting and be put on the link to n3. The second packet will not be in the queue at all. When both links have the same transmission delay, there will be no queueing delay at the second node.

In addition, each node will arrive at n3 at intervals equal to d_{trans}. As a generalized equation, the arrival time of $packet_n$ is equivalent to

$$d_{trans} * (n-1) + 2(d_{trans} + d_{prop})$$

This holds true for the first two tests, which use the same transmission delay and propagation delay for both links. Therefore, the arrival time of $packet_{1001}$ in the first test equals

$$.008 * (1001 - 1) + 2 * (.008 + .1) = 8.216$$

For the first two tests, the propagation delay dominates the total delay, simply because it is so much larger than the transmission delay.

In the case of the third test, there is a queueing delay at n2. This is because the bandwidth from n2 to n3 is 256 Kbps, while from n1 to n2, the bandwidth is 1 Mbps. Since the propagation delay is the same as the first test, the first packet will still arrive at n2 at .108 sceonds. However, the transmission delay at n2 is $8000/256000 = .03125$ seconds. The first packet will not be transmitted until .13925 seconds. When the second packet arrives at .116 seconds, it will have to wait in the queue until that time – a wait of .02325 seconds The second packet will not be transmitted by n2 until .1705 seconds, while the third packet will arrive at .124 seconds, a queue delay of .0465 seconds. The queue delay will keep increasing for each subsequent packet.

The queueing delay of $packet_n$ can be described by the equation

$$(n-1) * (.03125 - .008)$$

This is because each packet gets queued .008 seconds before the next packet, so the next packet has to wait .008 seconds less than if they had arrived at the same time. The equation for calculating the delay of $packet_n$ is

$$d_n = (n-1) * (.02325) + d_{trans1} + d_{trans2} + 2d_{prop}$$

The arrival time of $packet_{1001}$ is equal to the total delay added to the creation time, or

$$(1001-1) * (.02325) + .008 + .03125 + .2 + 8 = 31.48925$$

3 Queueing Theory

The project's final phase was to test the properties of an M/D/1 queue empirically using a simulated network at varying loads to test queueing delay growth.

3.1 Network Configuration

This test only required a node to send packets from and a network to receieve them, so the same network structure from the first part was used. The network was configured similarly to the networks first part of the first part of the project. The configuration is shown below:

```
# n1 -- n2
# network configuration
n1 n2
n2 n1

# link configuration
n1 n2 1Mbps 1ms
n2 n1 1Mbps 1ms
```

3.2 Testing Process

To test the queueing delay under varying loads, packets were randomly generated for a simulated 30 seconds. This was repeated 12 times, each at a different load percentage of the maximum load. The values used as loads modifiers were 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.78, 0.8, 0.9, 0.95, and 0.98. At higher loads, more packets were generated, with the idea being that queue times would grow exponentially. As each packet arrived, its queueing delay was stored in a file, such that each simulation run stored the data in a separate file.

As a separate process, to compare the recorded queueing delay with the theoretical delay, each file was parsed to find the average queueing delay in each iteration. The theoretical delay was calculated using the formula

$$\frac{1}{2\lambda} * \frac{\rho}{\rho - 1}$$

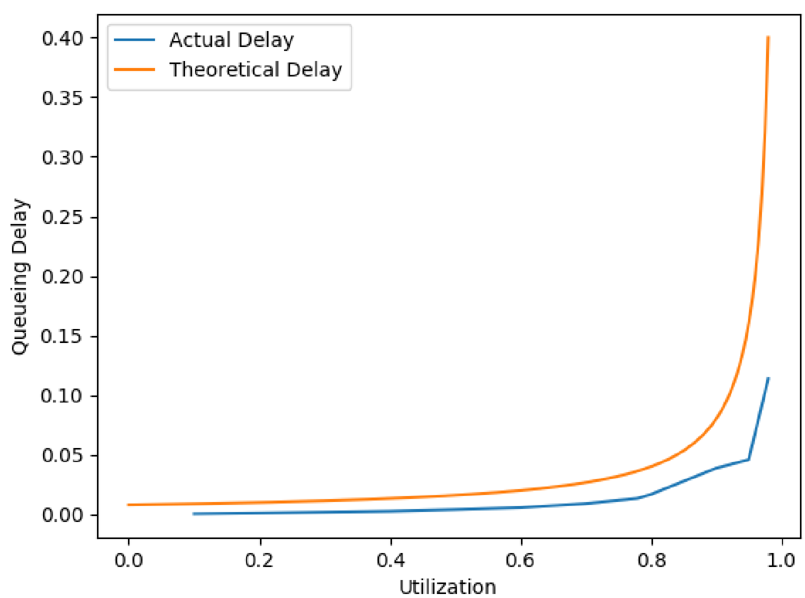
across many values of ρ from 0 to 1, exclusive. λ is substituted with $\rho * \mu$, where μ is the mean service rate, calculated by dividing the bandwidth by the packet size, or 1000000/8000.

3.3 Results

Network Utilization	Avg. Queueing Delay
.10	0.00047
.20	0.00111
.30	0.00189
.40	0.00267
.50	0.00409
.60	0.00570
.70	0.00904
.78	0.01345
.80	0.01670
.90	0.03873
.95	0.04590
.98	0.11373

3.4 Analysis

As expected, the queueing delay grew roughly exponentially with the utilization of the network. Even at 50% network utilization, the average queueing delay was just 0.0041 seconds. At 70% utilization, however, it jumps to 0.009, over twice as long. Then at 90%, it reaches 0.0387, and the average queueing delay at 98% is 0.1137 seconds, which is almost thirty times longer than at 50%, about half the load on the network. Interestingly, the delay only increases by 0.007 seconds from 90% utilization to 95%, which is much less than would be expected. Other than that, data point, the results indicate exponential growth, particularly apparent in the upper 10% utilization region. Compared to the theoretical growth, it is actually much slower growing than would be expected given the network parameters.



As seen in the chart, the theortical delay is greater than the actual delay at every point on the graph. Additionally, the actual results do not follow the expected results very closely. The theoretical plot begins rapidly increasing at around 95% utilization. This spot is a sort of anomoly for the actual results, where the discrepancy between the empirical results and the expected results is most noticeable. While the overall trend of the results follows the theoretical growth slightly, and more generally does trace an exponential curve, the difference is significant, and the divergance begins even at very low network utilization values.