CS460 Lab 1 Report: Network Simulation

Michael K. Eagar

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1 Two Nodes

I set up the two node network in the simulator by first creating the two nodes, n_1 and n_2. I then created the bidirectional link between them (using two unidirectional links in the simulator, $n_1 \rightarrow n_2$ and $n_2 \rightarrow n_1$). For the first scenario, the bidirectional link was created with bandwidth of 1 Mbps, and a propagation delay of 1 second:

Listing 1: Two Nodes Scenario 1

```
    # setup network
    # create nodes
    n1 = node.Node()
    n2 = node.Node()

    # create link from n1 to n2
    l = link.Link(address=1,startpoint=n1,endpoint=n2,bandwidth=1000000.0,propagation=1.0)
    n1.add_link(l)
    n1.add_forwarding_entry(address=2,link=l)

    # create link from n2 to n1
    l = link.Link(address=2,startpoint=n2,endpoint=n1,bandwidth=1000000.0,propagation=1.0)
    n2.add_link(l)
    n2.add_forwarding_entry(address=1,link=l)
```

Program output: 1.008 1 0 1.008 0.008 1.0 0
According to the simulation the total amount of time it took to send one 1000 byte packet from node 1 to node 2 was 1.008 sec.
The calculations below show the simulator to be correct:

$L = 8,000\ bits$

$R = 1,000,000\ bps$

$d_{prop} = 1\ sec$

$d_{trans} = \frac{L}{R} = \frac{8,000\ bits}{1,000,000\ bps} = 0.008\ sec$

$d_{total} = d_{prop} + d_{trans} = 1\ sec + 0.008\ sec = 1.008\ sec$

In the second scenario, the bandwidth was reduced to 100 bps with a propagation delay of 10 ms:

Listing 2: Two Nodes Scenario 2

```
    # setup network
    # create nodes
    n1 = node.Node()
    n2 = node.Node()
```

```python

    # create link from n1 to n2
    l = link.Link(address=1,startpoint=n1,endpoint=n2,bandwidth=100.0,propagation=0.01)
    n1.add_link(l)
    n1.add_forwarding_entry(address=2,link=l)

    # create link from n2 to n1
    l = link.Link(address=2,startpoint=n2,endpoint=n1,bandwidth=100.0,propagation=0.01)
    n2.add_link(l)
    n2.add_forwarding_entry(address=1,link=l)
```

Program output: 80.01 1 0 80.01 80.0 0.01 0
According to the simulation for this scenario, the total time taken to send one 1000 byte packet from node 1 to node 2 was 80.01 sec.
The calculations below show the simulator to be correct:

$L = 8,000\ bits$
$R = 100\ bps$
$d_{prop} = 10ms = 0.01\ sec$
$d_{trans} = \frac{L}{R} = \frac{8{,}000\ bits}{100\ bps} = 80\ sec$
$d_{total} = d_{prop} + d_{trans} = 80\ sec + 0.01\ sec = 80.01\ sec$

For the third scenario, the bandwidth was increased back to 1 Mbps, but the propagation delay was kept at 10 ms:

Listing 3: Two Nodes Scenario 3

```python
    # setup network
    # create nodes
    n1 = node.Node()
    n2 = node.Node()

    # create link from n1 to n2
    l = link.Link(address=1,startpoint=n1,endpoint=n2,bandwidth=1000000.0,propagation=0.01)
    n1.add_link(l)
    n1.add_forwarding_entry(address=2,link=l)

    # create link from n2 to n1
    l = link.Link(address=2,startpoint=n2,endpoint=n1,bandwidth=1000000.0,propagation=0.01)
    n2.add_link(l)
    n2.add_forwarding_entry(address=1,link=l)
```

Program output:

0.018 1 0 0.018 0.008 0.01 0
0.026 2 0 0.026 0.008 0.01 0.008
0.034 3 0 0.034 0.008 0.01 0.016
2.018 4 2.0 0.018 0.008 0.01 0.0

The simulator shows that it takes one 1000 byte packet 0.018 sec to travel from node 1 to node 2 along this link.
The calculations below show this to be correct:

$L = 8,000\ bits$

$R = 1,000,000\ bps$
$d_{prop} = 10ms = 0.01\ sec$
$d_{trans} = \frac{L}{R} = \frac{8{,}000\ bits}{1{,}000{,}000\ bps} = 0.008\ sec$
$d_{total} = d_{prop} + d_{trans} = 0.008\ sec + 0.01\ sec = 0.018\ sec$

From the output we can see that the 1^{st} and 4^{th} packets have no queuing delay (the last number on their respective lines) while packets #2 and #3 have queuing delay of 0.008 sec and 0.016 sec respectively. These two accumulate the delay because packets 1 through 3 are all sent at $time = 0\ sec$, so #2 has to wait for packet #1 to transmit, and #3 for both #1 and #2 to transmit completely. Packet #4 doesn't get sent until $time = 2.0\ sec$, so there are no other packets in queue or being transmitted, and it is transmitted right away.

Total time for each packet is: #1 - 0.018 sec, #2 - 0.026 sec, #3 - 0.034 sec, #4 - 2.018 sec

2 Three Nodes

Scenario 1 - Two Fast Links

To set up this three node network in the simulator, I first created the three nodes: n_1, n_2, and n_3. I then set up the fast 1 Mbps links connecting the three nodes. I created the links as follows: $n_1 \rightarrow n_2$, $n_2 \rightarrow n_1$, $n_2 \rightarrow n_3$, and $n_3 \rightarrow n_2$. Each link has a propagation delay of 100 ms.

Listing 4: Three Nodes Scenario 1a

```
# setup network
n1 = node.Node()
n2 = node.Node()
n3 = node.Node()

# create link from 1 to 2
l = link.Link(address=1,startpoint=n1,endpoint=n2,bandwidth=1000000.0,
    propagation=0.1)
n1.add_link(l)
n1.add_forwarding_entry(address=2,link=l)
n1.add_forwarding_entry(address=3,link=l)

# create link from 2 to 1
l = link.Link(address=2,startpoint=n2,endpoint=n1,bandwidth=1000000.0,
    propagation=0.1)
n2.add_link(l)
n2.add_forwarding_entry(address=1,link=l)

# create link from 2 to 3
l = link.Link(address=2,startpoint=n2,endpoint=n3,bandwidth=1000000.0,
    propagation=0.1)
n2.add_link(l)
n2.add_forwarding_entry(address=3,link=l)

# create link from 3 to 2
l = link.Link(address=3,startpoint=n3,endpoint=n2,bandwidth=1000000.0,
    propagation=0.1)
n3.add_link(l)
n3.add_forwarding_entry(address=2,link=l)
n3.add_forwarding_entry(address=1,link=l)
```

Part A

Node A transmits a stream of 1 kB packets to node C. How long does it take to transfer a 1 MB file, divided into 1 kB packets, from A to C? Which type of delay dominates?

It will take 8.208 sec to fully transfer a 1 MB file divided into 1,000 1 KB packets from node A to node C. Transmission delay accounts for 8.008 sec of the time taken to transfer the file, while propagation delay only accounts for 0.2 sec. Therefore, transmission delay (d_{trans}) dominates. This matches the output of the simulator (see below), thus proving the simulator correct.

Part B

Network setup for part B is the same as for part A, except that the links' bandwidths were changed to 1 Gbps. Propagation delays remained at 100 ms.

Listing 5: Three Nodes Scenario 1b

```
    l = link.Link(address=1,startpoint=n1,endpoint=n2,bandwidth=1000000000.0,
        propagation=0.1)
```

If both links are upgraded to a rate of 1 Gbps, how long does it take to transfer a 1 MB file from A to C?

If both links are upgraded to a rate of 1 Gbps then it will only take 0.208008 sec to transfer a 1 MB file from node A to node C.

Scenario 2 - One Fast and One Slow Link

To set up the second three node network, I created the three nodes just like before, but when setting up the links between the nodes I created them as follows.

Fast links (1 Mbps, 100ms d_{prop}): $n_1 \rightarrow n_2$ and $n_2 \rightarrow n_1$

Slow links (256 Kbps, 100ms d_{prop}): $n_2 \rightarrow n_3$, and $n_3 \rightarrow n_2$

The links between node B and node C have had their bandwidth reduced to 256 Kbps, but the propagation delay remains the same.

Listing 6: Three Nodes Scenario 2

```
    # setup network
    n1 = node.Node()
    n2 = node.Node()
    n3 = node.Node()
    # create link from 1 to 2
    l = link.Link(address=1,startpoint=n1,endpoint=n2,bandwidth=1000000.0,
        propagation=0.1)
    n1.add_link(l)
    n1.add_forwarding_entry(address=2,link=l)
    n1.add_forwarding_entry(address=3,link=l)
    # create link from 2 to 1
    l = link.Link(address=2,startpoint=n2,endpoint=n1,bandwidth=1000000.0,
        propagation=0.1)
    n2.add_link(l)
    n2.add_forwarding_entry(address=1,link=l)
    # create link from 2 to 3
    l = link.Link(address=2,startpoint=n2,endpoint=n3,bandwidth=256000.0,
        propagation=0.1)
    n2.add_link(l)
    n2.add_forwarding_entry(address=3,link=l)
    # create link from 3 to 2
```

```
    l = link.Link(address=3,startpoint=n3,endpoint=n2,bandwidth=256000.0,
        propagation=0.1)
    n3.add_link(l)
    n3.add_forwarding_entry(address=2,link=l)
    n3.add_forwarding_entry(address=1,link=l)

    d = DelayHandler()
    n3.add_protocol(protocol="delay",handler=d)
```

Node A transmits 1000 packets, each of size 1 kB, to node C. How long would it does it take to transfer a 1 MB file, divided into 1 kB packets, from A to C? It would take 31.458 sec to transfer a 1 MB file divided into one thousand 1 kB packets from node A to node C. In order to ensure that there was no queuing delay at node A in the simulation for this network, I created each packet to be sent at successively later times (the transmission delay for the link from A to B multiplied by the packet #). This caused the only queuing delay in the system to occur at node B.

Below is the output from the simulator for Scenario 2. I know it is correct because of the calculations involving the last packet of the file. The 1000^{th} packet is transmitted at 7.992 sec(t_{trans}). Transmission time at node A is 8 ms (or 0.008 seconds), and at node B is 31.25 ms (or 0.03125 sec) for a total transmission delay of 0.03925 seconds (d_{trans}). $d_{prop} = 0.2\ sec$ total for both links, and the last packet's queuing delay at node B is 23.22675 sec. For the last packet, $t_{trans} + d_{trans} + d_{prop} + d_{queue} = Time_{trans}$ for the entire file. This works out as follows:

$$t_{trans} + d_{trans} + d_{prop} + d_{queue} = 7.992\ sec + 0.03925\ sec + 0.2\ sec + 23.22675\ sec = 31.458\ sec$$

total transmission time for a 1 MB file.

Listing 7: Three Nodes Scenario 2 output

```
0.23925 0 0 0.23925 0.03925 0.2 0.0
0.2705 1 0.008 0.2625 0.03925 0.2 0.02325
0.30175 2 0.016 0.28575 0.03925 0.2 0.0465
0.333 3 0.024 0.309 0.03925 0.2 0.06975
0.36425 4 0.032 0.33225 0.03925 0.2 0.093
0.3955 5 0.04 0.3555 0.03925 0.2 0.11625
0.42675 6 0.048 0.37875 0.03925 0.2 0.1395
0.458 7 0.056 0.402 0.03925 0.2 0.16275
0.48925 8 0.064 0.42525 0.03925 0.2 0.186
0.5205 9 0.072 0.4485 0.03925 0.2 0.20925
0.55175 10 0.08 0.47175 0.03925 0.2 0.2325
0.583 11 0.088 0.495 0.03925 0.2 0.25575
0.61425 12 0.096 0.51825 0.03925 0.2 0.279
0.6455 13 0.104 0.5415 0.03925 0.2 0.30225
0.67675 14 0.112 0.56475 0.03925 0.2 0.3255
0.708 15 0.12 0.588 0.03925 0.2 0.34875
0.73925 16 0.128 0.61125 0.03925 0.2 0.372
0.7705 17 0.136 0.6345 0.03925 0.2 0.39525
0.80175 18 0.144 0.65775 0.03925 0.2 0.4185
0.833 19 0.152 0.681 0.03925 0.2 0.44175
0.86425 20 0.16 0.70425 0.03925 0.2 0.465
0.8955 21 0.168 0.7275 0.03925 0.2 0.48825
0.92675 22 0.176 0.75075 0.03925 0.2 0.5115
0.958 23 0.184 0.774 0.03925 0.2 0.53475
0.98925 24 0.192 0.79725 0.03925 0.2 0.558
1.0205 25 0.2 0.8205 0.03925 0.2 0.58125
```

```
1.05175 26 0.208 0.84375 0.03925 0.2 0.6045
1.083 27 0.216 0.867 0.03925 0.2 0.62775
1.11425 28 0.224 0.89025 0.03925 0.2 0.651
1.1455 29 0.232 0.9135 0.03925 0.2 0.67425
1.17675 30 0.24 0.93675 0.03925 0.2 0.6975
1.208 31 0.248 0.96 0.03925 0.2 0.72075
1.23925 32 0.256 0.98325 0.03925 0.2 0.744
1.2705 33 0.264 1.0065 0.03925 0.2 0.76725
1.30175 34 0.272 1.02975 0.03925 0.2 0.7905
1.333 35 0.28 1.053 0.03925 0.2 0.81375
1.36425 36 0.288 1.07625 0.03925 0.2 0.837
1.3955 37 0.296 1.0995 0.03925 0.2 0.86025
1.42675 38 0.304 1.12275 0.03925 0.2 0.8835
1.458 39 0.312 1.146 0.03925 0.2 0.90675
1.48925 40 0.32 1.16925 0.03925 0.2 0.93
1.5205 41 0.328 1.1925 0.03925 0.2 0.95325
1.55175 42 0.336 1.21575 0.03925 0.2 0.9765
1.583 43 0.344 1.239 0.03925 0.2 0.99975
1.61425 44 0.352 1.26225 0.03925 0.2 1.023
1.6455 45 0.36 1.2855 0.03925 0.2 1.04625
1.67675 46 0.368 1.30875 0.03925 0.2 1.0695
1.708 47 0.376 1.332 0.03925 0.2 1.09275
1.73925 48 0.384 1.35525 0.03925 0.2 1.116
1.7705 49 0.392 1.3785 0.03925 0.2 1.13925
1.80175 50 0.4 1.40175 0.03925 0.2 1.1625
1.833 51 0.408 1.425 0.03925 0.2 1.18575
1.86425 52 0.416 1.44825 0.03925 0.2 1.209
1.8955 53 0.424 1.4715 0.03925 0.2 1.23225
1.92675 54 0.432 1.49475 0.03925 0.2 1.2555
1.958 55 0.44 1.518 0.03925 0.2 1.27875
1.98925 56 0.448 1.54125 0.03925 0.2 1.302
2.0205 57 0.456 1.5645 0.03925 0.2 1.32525
2.05175 58 0.464 1.58775 0.03925 0.2 1.3485
2.083 59 0.472 1.611 0.03925 0.2 1.37175
2.11425 60 0.48 1.63425 0.03925 0.2 1.395
2.1455 61 0.488 1.6575 0.03925 0.2 1.41825
2.17675 62 0.496 1.68075 0.03925 0.2 1.4415
2.208 63 0.504 1.704 0.03925 0.2 1.46475
2.23925 64 0.512 1.72725 0.03925 0.2 1.488
2.2705 65 0.52 1.7505 0.03925 0.2 1.51125
2.30175 66 0.528 1.77375 0.03925 0.2 1.5345
2.333 67 0.536 1.797 0.03925 0.2 1.55775
2.36425 68 0.544 1.82025 0.03925 0.2 1.581
2.3955 69 0.552 1.8435 0.03925 0.2 1.60425
2.42675 70 0.56 1.86675 0.03925 0.2 1.6275
2.458 71 0.568 1.89 0.03925 0.2 1.65075
2.48925 72 0.576 1.91325 0.03925 0.2 1.674
2.5205 73 0.584 1.9365 0.03925 0.2 1.69725
2.55175 74 0.592 1.95975 0.03925 0.2 1.7205
2.583 75 0.6 1.983 0.03925 0.2 1.74375
2.61425 76 0.608 2.00625 0.03925 0.2 1.767
2.6455 77 0.616 2.0295 0.03925 0.2 1.79025
2.67675 78 0.624 2.05275 0.03925 0.2 1.8135
2.708 79 0.632 2.076 0.03925 0.2 1.83675
2.73925 80 0.64 2.09925 0.03925 0.2 1.86
2.7705 81 0.648 2.1225 0.03925 0.2 1.88325
2.80175 82 0.656 2.14575 0.03925 0.2 1.9065
```

```
2.833 83 0.664 2.169 0.03925 0.2 1.92975
2.86425 84 0.672 2.19225 0.03925 0.2 1.953
2.8955 85 0.68 2.2155 0.03925 0.2 1.97625
2.92675 86 0.688 2.23875 0.03925 0.2 1.9995
2.958 87 0.696 2.262 0.03925 0.2 2.02275
2.98925 88 0.704 2.28525 0.03925 0.2 2.046
3.0205 89 0.712 2.3085 0.03925 0.2 2.06925
3.05175 90 0.72 2.33175 0.03925 0.2 2.0925
3.083 91 0.728 2.355 0.03925 0.2 2.11575
3.11425 92 0.736 2.37825 0.03925 0.2 2.139
3.1455 93 0.744 2.4015 0.03925 0.2 2.16225
3.17675 94 0.752 2.42475 0.03925 0.2 2.1855
3.208 95 0.76 2.448 0.03925 0.2 2.20875
3.23925 96 0.768 2.47125 0.03925 0.2 2.232
3.2705 97 0.776 2.4945 0.03925 0.2 2.25525
3.30175 98 0.784 2.51775 0.03925 0.2 2.2785
3.333 99 0.792 2.541 0.03925 0.2 2.30175
3.36425 100 0.8 2.56425 0.03925 0.2 2.325
3.3955 101 0.808 2.5875 0.03925 0.2 2.34825
3.42675 102 0.816 2.61075 0.03925 0.2 2.3715
3.458 103 0.824 2.634 0.03925 0.2 2.39475
3.48925 104 0.832 2.65725 0.03925 0.2 2.418
3.5205 105 0.84 2.6805 0.03925 0.2 2.44125
3.55175 106 0.848 2.70375 0.03925 0.2 2.4645
3.583 107 0.856 2.727 0.03925 0.2 2.48775
3.61425 108 0.864 2.75025 0.03925 0.2 2.511
3.6455 109 0.872 2.7735 0.03925 0.2 2.53425
3.67675 110 0.88 2.79675 0.03925 0.2 2.5575
3.708 111 0.888 2.82 0.03925 0.2 2.58075
3.73925 112 0.896 2.84325 0.03925 0.2 2.604
3.7705 113 0.904 2.8665 0.03925 0.2 2.62725
3.80175 114 0.912 2.88975 0.03925 0.2 2.6505
3.833 115 0.92 2.913 0.03925 0.2 2.67375
3.86425 116 0.928 2.93625 0.03925 0.2 2.697
3.8955 117 0.936 2.9595 0.03925 0.2 2.72025
3.92675 118 0.944 2.98275 0.03925 0.2 2.7435
3.958 119 0.952 3.006 0.03925 0.2 2.76675
3.98925 120 0.96 3.02925 0.03925 0.2 2.79
4.0205 121 0.968 3.0525 0.03925 0.2 2.81325
4.05175 122 0.976 3.07575 0.03925 0.2 2.8365
4.083 123 0.984 3.099 0.03925 0.2 2.85975
4.11425 124 0.992 3.12225 0.03925 0.2 2.883
4.1455 125 1.0 3.1455 0.03925 0.2 2.90625
4.17675 126 1.008 3.16875 0.03925 0.2 2.9295
4.208 127 1.016 3.192 0.03925 0.2 2.95275
4.23925 128 1.024 3.21525 0.03925 0.2 2.976
4.2705 129 1.032 3.2385 0.03925 0.2 2.99925
4.30175 130 1.04 3.26175 0.03925 0.2 3.0225
4.333 131 1.048 3.285 0.03925 0.2 3.04575
4.36425 132 1.056 3.30825 0.03925 0.2 3.069
4.3955 133 1.064 3.3315 0.03925 0.2 3.09225
4.42675 134 1.072 3.35475 0.03925 0.2 3.1155
4.458 135 1.08 3.378 0.03925 0.2 3.13875
4.48925 136 1.088 3.40125 0.03925 0.2 3.162
4.5205 137 1.096 3.4245 0.03925 0.2 3.18525
4.55175 138 1.104 3.44775 0.03925 0.2 3.2085
4.583 139 1.112 3.471 0.03925 0.2 3.23175
```

```
4.61425 140 1.12 3.49425 0.03925 0.2 3.255
4.6455 141 1.128 3.5175 0.03925 0.2 3.27825
4.67675 142 1.136 3.54075 0.03925 0.2 3.3015
4.708 143 1.144 3.564 0.03925 0.2 3.32475
4.73925 144 1.152 3.58725 0.03925 0.2 3.348
4.7705 145 1.16 3.6105 0.03925 0.2 3.37125
4.80175 146 1.168 3.63375 0.03925 0.2 3.3945
4.833 147 1.176 3.657 0.03925 0.2 3.41775
4.86425 148 1.184 3.68025 0.03925 0.2 3.441
4.8955 149 1.192 3.7035 0.03925 0.2 3.46425
4.92675 150 1.2 3.72675 0.03925 0.2 3.4875
4.958 151 1.208 3.75 0.03925 0.2 3.51075
4.98925 152 1.216 3.77325 0.03925 0.2 3.534
5.0205 153 1.224 3.7965 0.03925 0.2 3.55725
5.05175 154 1.232 3.81975 0.03925 0.2 3.5805
5.083 155 1.24 3.843 0.03925 0.2 3.60375
5.11425 156 1.248 3.86625 0.03925 0.2 3.627
5.1455 157 1.256 3.8895 0.03925 0.2 3.65025
5.17675 158 1.264 3.91275 0.03925 0.2 3.6735
5.208 159 1.272 3.936 0.03925 0.2 3.69675
5.23925 160 1.28 3.95925 0.03925 0.2 3.72
5.2705 161 1.288 3.9825 0.03925 0.2 3.74325
5.30175 162 1.296 4.00575 0.03925 0.2 3.7665
5.333 163 1.304 4.029 0.03925 0.2 3.78975
5.36425 164 1.312 4.05225 0.03925 0.2 3.813
5.3955 165 1.32 4.0755 0.03925 0.2 3.83625
5.42675 166 1.328 4.09875 0.03925 0.2 3.8595
5.458 167 1.336 4.122 0.03925 0.2 3.88275
5.48925 168 1.344 4.14525 0.03925 0.2 3.906
5.5205 169 1.352 4.1685 0.03925 0.2 3.92925
5.55175 170 1.36 4.19175 0.03925 0.2 3.9525
5.583 171 1.368 4.215 0.03925 0.2 3.97575
5.61425 172 1.376 4.23825 0.03925 0.2 3.999
5.6455 173 1.384 4.2615 0.03925 0.2 4.02225
5.67675 174 1.392 4.28475 0.03925 0.2 4.0455
5.708 175 1.4 4.308 0.03925 0.2 4.06875
5.73925 176 1.408 4.33125 0.03925 0.2 4.092
5.7705 177 1.416 4.3545 0.03925 0.2 4.11525
5.80175 178 1.424 4.37775 0.03925 0.2 4.1385
5.833 179 1.432 4.401 0.03925 0.2 4.16175
5.86425 180 1.44 4.42425 0.03925 0.2 4.185
5.8955 181 1.448 4.4475 0.03925 0.2 4.20825
5.92675 182 1.456 4.47075 0.03925 0.2 4.2315
5.958 183 1.464 4.494 0.03925 0.2 4.25475
5.98925 184 1.472 4.51725 0.03925 0.2 4.278
6.0205 185 1.48 4.5405 0.03925 0.2 4.30125
6.05175 186 1.488 4.56375 0.03925 0.2 4.3245
6.083 187 1.496 4.587 0.03925 0.2 4.34775
6.11425 188 1.504 4.61025 0.03925 0.2 4.371
6.1455 189 1.512 4.6335 0.03925 0.2 4.39425
6.17675 190 1.52 4.65675 0.03925 0.2 4.4175
6.208 191 1.528 4.68 0.03925 0.2 4.44075
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26.5205 841 6.728 19.7925 0.03925 0.2 19.55325
26.55175 842 6.736 19.81575 0.03925 0.2 19.5765
26.583 843 6.744 19.839 0.03925 0.2 19.59975
26.61425 844 6.752 19.86225 0.03925 0.2 19.623
26.6455 845 6.76 19.8855 0.03925 0.2 19.64625
26.67675 846 6.768 19.90875 0.03925 0.2 19.6695
26.708 847 6.776 19.932 0.03925 0.2 19.69275
26.73925 848 6.784 19.95525 0.03925 0.2 19.716
26.7705 849 6.792 19.9785 0.03925 0.2 19.73925
26.80175 850 6.8 20.00175 0.03925 0.2 19.7625
26.833 851 6.808 20.025 0.03925 0.2 19.78575
26.86425 852 6.816 20.04825 0.03925 0.2 19.809
26.8955 853 6.824 20.0715 0.03925 0.2 19.83225
26.92675 854 6.832 20.09475 0.03925 0.2 19.8555
26.958 855 6.84 20.118 0.03925 0.2 19.87875
26.98925 856 6.848 20.14125 0.03925 0.2 19.902
27.0205 857 6.856 20.1645 0.03925 0.2 19.92525
27.05175 858 6.864 20.18775 0.03925 0.2 19.9485
27.083 859 6.872 20.211 0.03925 0.2 19.97175
27.11425 860 6.88 20.23425 0.03925 0.2 19.995
27.1455 861 6.888 20.2575 0.03925 0.2 20.01825
27.17675 862 6.896 20.28075 0.03925 0.2 20.0415
27.208 863 6.904 20.304 0.03925 0.2 20.06475
27.23925 864 6.912 20.32725 0.03925 0.2 20.088
27.2705 865 6.92 20.3505 0.03925 0.2 20.11125
27.30175 866 6.928 20.37375 0.03925 0.2 20.1345
27.333 867 6.936 20.397 0.03925 0.2 20.15775
27.36425 868 6.944 20.42025 0.03925 0.2 20.181
27.3955 869 6.952 20.4435 0.03925 0.2 20.20425
27.42675 870 6.96 20.46675 0.03925 0.2 20.2275
27.458 871 6.968 20.49 0.03925 0.2 20.25075
27.48925 872 6.976 20.51325 0.03925 0.2 20.274
27.5205 873 6.984 20.5365 0.03925 0.2 20.29725
27.55175 874 6.992 20.55975 0.03925 0.2 20.3205
27.583 875 7.0 20.583 0.03925 0.2 20.34375
27.61425 876 7.008 20.60625 0.03925 0.2 20.367
27.6455 877 7.016 20.6295 0.03925 0.2 20.39025
27.67675 878 7.024 20.65275 0.03925 0.2 20.4135
27.708 879 7.032 20.676 0.03925 0.2 20.43675
27.73925 880 7.04 20.69925 0.03925 0.2 20.46
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27.7705 881 7.048 20.7225 0.03925 0.2 20.48325
27.80175 882 7.056 20.74575 0.03925 0.2 20.5065
27.833 883 7.064 20.769 0.03925 0.2 20.52975
27.86425 884 7.072 20.79225 0.03925 0.2 20.553
27.8955 885 7.08 20.8155 0.03925 0.2 20.57625
27.92675 886 7.088 20.83875 0.03925 0.2 20.5995
27.958 887 7.096 20.862 0.03925 0.2 20.62275
27.98925 888 7.104 20.88525 0.03925 0.2 20.646
28.0205 889 7.112 20.9085 0.03925 0.2 20.66925
28.05175 890 7.12 20.93175 0.03925 0.2 20.6925
28.083 891 7.128 20.955 0.03925 0.2 20.71575
28.11425 892 7.136 20.97825 0.03925 0.2 20.739
28.1455 893 7.144 21.0015 0.03925 0.2 20.76225
28.17675 894 7.152 21.02475 0.03925 0.2 20.7855
28.208 895 7.16 21.048 0.03925 0.2 20.80875
28.23925 896 7.168 21.07125 0.03925 0.2 20.832
28.2705 897 7.176 21.0945 0.03925 0.2 20.85525
28.30175 898 7.184 21.11775 0.03925 0.2 20.8785
28.333 899 7.192 21.141 0.03925 0.2 20.90175
28.36425 900 7.2 21.16425 0.03925 0.2 20.925
28.3955 901 7.208 21.1875 0.03925 0.2 20.94825
28.42675 902 7.216 21.21075 0.03925 0.2 20.9715
28.458 903 7.224 21.234 0.03925 0.2 20.99475
28.48925 904 7.232 21.25725 0.03925 0.2 21.018
28.5205 905 7.24 21.2805 0.03925 0.2 21.04125
28.55175 906 7.248 21.30375 0.03925 0.2 21.0645
28.583 907 7.256 21.327 0.03925 0.2 21.08775
28.61425 908 7.264 21.35025 0.03925 0.2 21.111
28.6455 909 7.272 21.3735 0.03925 0.2 21.13425
28.67675 910 7.28 21.39675 0.03925 0.2 21.1575
28.708 911 7.288 21.42 0.03925 0.2 21.18075
28.73925 912 7.296 21.44325 0.03925 0.2 21.204
28.7705 913 7.304 21.4665 0.03925 0.2 21.22725
28.80175 914 7.312 21.48975 0.03925 0.2 21.2505
28.833 915 7.32 21.513 0.03925 0.2 21.27375
28.86425 916 7.328 21.53625 0.03925 0.2 21.297
28.8955 917 7.336 21.5595 0.03925 0.2 21.32025
28.92675 918 7.344 21.58275 0.03925 0.2 21.3435
28.958 919 7.352 21.606 0.03925 0.2 21.36675
28.98925 920 7.36 21.62925 0.03925 0.2 21.39
29.0205 921 7.368 21.6525 0.03925 0.2 21.41325
29.05175 922 7.376 21.67575 0.03925 0.2 21.4365
29.083 923 7.384 21.699 0.03925 0.2 21.45975
29.11425 924 7.392 21.72225 0.03925 0.2 21.483
29.1455 925 7.4 21.7455 0.03925 0.2 21.50625
29.17675 926 7.408 21.76875 0.03925 0.2 21.5295
29.208 927 7.416 21.792 0.03925 0.2 21.55275
29.23925 928 7.424 21.81525 0.03925 0.2 21.576
29.2705 929 7.432 21.8385 0.03925 0.2 21.59925
29.30175 930 7.44 21.86175 0.03925 0.2 21.6225
29.333 931 7.448 21.885 0.03925 0.2 21.64575
29.36425 932 7.456 21.90825 0.03925 0.2 21.669
29.3955 933 7.464 21.9315 0.03925 0.2 21.69225
29.42675 934 7.472 21.95475 0.03925 0.2 21.7155
29.458 935 7.48 21.978 0.03925 0.2 21.73875
29.48925 936 7.488 22.00125 0.03925 0.2 21.762
29.5205 937 7.496 22.0245 0.03925 0.2 21.78525
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29.55175 938 7.504 22.04775 0.03925 0.2 21.8085
29.583 939 7.512 22.071 0.03925 0.2 21.83175
29.61425 940 7.52 22.09425 0.03925 0.2 21.855
29.6455 941 7.528 22.1175 0.03925 0.2 21.87825
29.67675 942 7.536 22.14075 0.03925 0.2 21.9015
29.708 943 7.544 22.164 0.03925 0.2 21.92475
29.73925 944 7.552 22.18725 0.03925 0.2 21.948
29.7705 945 7.56 22.2105 0.03925 0.2 21.97125
29.80175 946 7.568 22.23375 0.03925 0.2 21.9945
29.833 947 7.576 22.257 0.03925 0.2 22.01775
29.86425 948 7.584 22.28025 0.03925 0.2 22.041
29.8955 949 7.592 22.3035 0.03925 0.2 22.06425
29.92675 950 7.6 22.32675 0.03925 0.2 22.0875
29.958 951 7.608 22.35 0.03925 0.2 22.11075
29.98925 952 7.616 22.37325 0.03925 0.2 22.134
30.0205 953 7.624 22.3965 0.03925 0.2 22.15725
30.05175 954 7.632 22.41975 0.03925 0.2 22.1805
30.083 955 7.64 22.443 0.03925 0.2 22.20375
30.11425 956 7.648 22.46625 0.03925 0.2 22.227
30.1455 957 7.656 22.4895 0.03925 0.2 22.25025
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30.23925 960 7.68 22.55925 0.03925 0.2 22.32
30.2705 961 7.688 22.5825 0.03925 0.2 22.34325
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30.333 963 7.704 22.629 0.03925 0.2 22.38975
30.36425 964 7.712 22.65225 0.03925 0.2 22.413
30.3955 965 7.72 22.6755 0.03925 0.2 22.43625
30.42675 966 7.728 22.69875 0.03925 0.2 22.4595
30.458 967 7.736 22.722 0.03925 0.2 22.48275
30.48925 968 7.744 22.74525 0.03925 0.2 22.506
30.5205 969 7.752 22.7685 0.03925 0.2 22.52925
30.55175 970 7.76 22.79175 0.03925 0.2 22.5525
30.583 971 7.768 22.815 0.03925 0.2 22.57575
30.61425 972 7.776 22.83825 0.03925 0.2 22.599
30.6455 973 7.784 22.8615 0.03925 0.2 22.62225
30.67675 974 7.792 22.88475 0.03925 0.2 22.6455
30.708 975 7.8 22.908 0.03925 0.2 22.66875
30.73925 976 7.808 22.93125 0.03925 0.2 22.692
30.7705 977 7.816 22.9545 0.03925 0.2 22.71525
30.80175 978 7.824 22.97775 0.03925 0.2 22.7385
30.833 979 7.832 23.001 0.03925 0.2 22.76175
30.86425 980 7.84 23.02425 0.03925 0.2 22.785
30.8955 981 7.848 23.0475 0.03925 0.2 22.80825
30.92675 982 7.856 23.07075 0.03925 0.2 22.8315
30.958 983 7.864 23.094 0.03925 0.2 22.85475
30.98925 984 7.872 23.11725 0.03925 0.2 22.878
31.0205 985 7.88 23.1405 0.03925 0.2 22.90125
31.05175 986 7.888 23.16375 0.03925 0.2 22.9245
31.083 987 7.896 23.187 0.03925 0.2 22.94775
31.11425 988 7.904 23.21025 0.03925 0.2 22.971
31.1455 989 7.912 23.2335 0.03925 0.2 22.99425
31.17675 990 7.92 23.25675 0.03925 0.2 23.0175
31.208 991 7.928 23.28 0.03925 0.2 23.04075
31.23925 992 7.936 23.30325 0.03925 0.2 23.064
31.2705 993 7.944 23.3265 0.03925 0.2 23.08725
31.30175 994 7.952 23.34975 0.03925 0.2 23.1105
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31.333 995 7.96 23.373 0.03925 0.2 23.13375
31.36425 996 7.968 23.39625 0.03925 0.2 23.157
31.3955 997 7.976 23.4195 0.03925 0.2 23.18025
31.42675 998 7.984 23.44275 0.03925 0.2 23.2035
31.458 999 7.992 23.466 0.03925 0.2 23.22675
```

3 Queuing Delay

Experiment Setup

Below is the basic code I used to generate the data for this experiment. In order to generate varying loads, I changed the value of the *load_scale* variable on line 53, running the experiment with loads from 0.1 to 0.9, increasing in increments of 0.1, as well as at loads of 0.95 and 0.98. I set the duration for the load to 30 seconds in order to collect a larger amount of data in order to give a better estimate for my averages for queuing delay.
For each load, the script generated a large number of 1 kB packets and simulated transmitting them along a 1 Mbps link. The packets had randomly generated start times, and because of the large amount generated, queuing delay at the transmitting node was ensured. In order to collect the data from the simulation, I redirected *stdout* to a file when running the python script for each load level. These are saved in the textitqueuingtheory directory as queing10.out through queuing98.out.

Queuing Delay Code

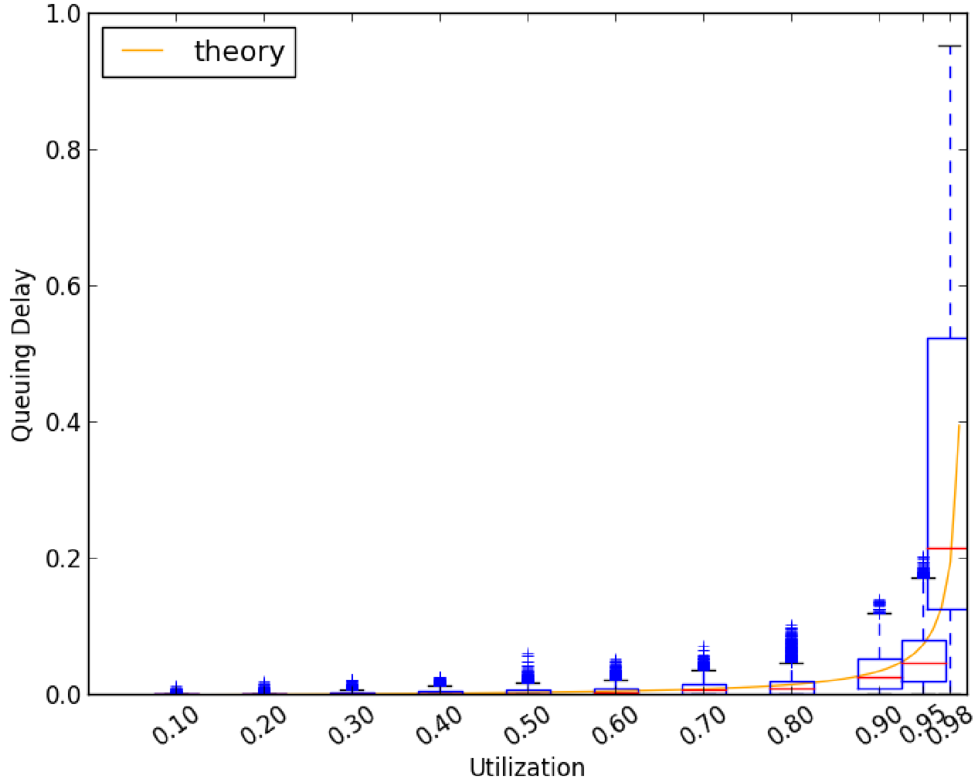
Listing 8: queuingdelay.py

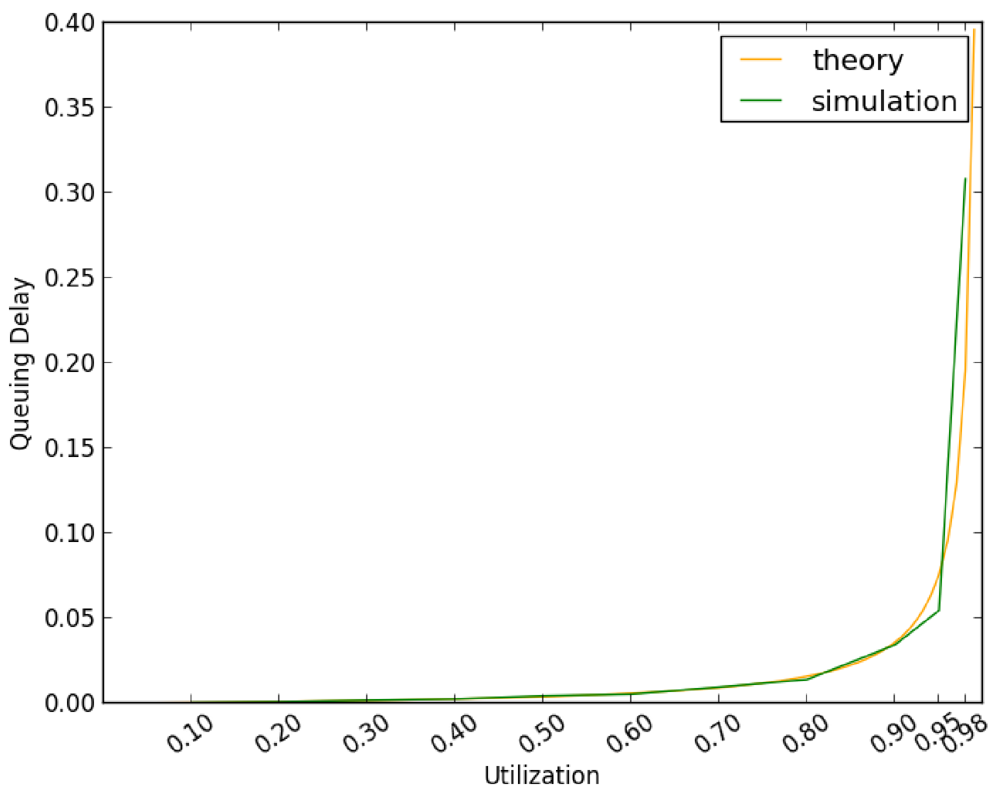
```
1 import sys
2 sys.path.append('../../../bene')
3
4 from src.sim import Sim
5 from src import node
6 from src import link
7 from src import packet
8
9 import random
10
11 class Generator(object):
12     def __init__(self,node,load,duration):
13         self.node = node
14         self.load = load
15         self.duration = duration
16         self.start = 0
17         self.ident = 1
18
19     def handle(self,event):
20         # quit if done
21         now = Sim.scheduler.current_time()
22         if (now - self.start) > self.duration:
23             return
24
25         # generate a packet
26         self.ident += 1
27         p = packet.Packet(destination_address=2,ident=self.ident,protocol='delay',length=1000)
28         Sim.scheduler.add(delay=0, event=p, handler=self.node.handle_packet)
29         # schedule the next time we should generate a packet
```

```
        Sim.scheduler.add(delay=random.expovariate(self.load), event='generate', handler=self.handle)

class DelayHandler(object):
    def handle_packet(self,packet):
        print Sim.scheduler.current_time(),packet.ident,packet.created,Sim.scheduler.current_time() - packet.created,packet.transmission_delay,packet.propagation_delay,packet.queueing_delay

if __name__ == '__main__':
    # parameters
    Sim.scheduler.reset()

    # setup network
    n1 = node.Node()
    n2 = node.Node()
    l = link.Link(address=1,startpoint=n1,endpoint=n2)
    n1.add_link(l)
    n1.add_forwarding_entry(address=2,link=l)
    l = link.Link(address=2,startpoint=n2,endpoint=n1)
    n2.add_link(l)
    n2.add_forwarding_entry(address=1,link=l)
    d = DelayHandler()
    n2.add_protocol(protocol="delay",handler=d)

    # setup packet generator
    load_scale = 0.8
    max_rate = 1000000/(1000*8)
    load = load_scale*max_rate
    g = Generator(node=n1, load=load,duration=30)
    Sim.scheduler.add(delay=0, event='generate', handler=g.handle)

    # run the simulation
    Sim.scheduler.run()
```

Queuing Delay Plots

As can be seen in the plots below, the simulation data matched the theoretical values of queuing delay quite well. It only really starts to deviate from the theory at the highest load values, near 95 and 98 percent loads. I think this small amount of difference could even be eliminated by increasing the duration of the simulation and collecting additional data.


theory
1.0
0.8
0.6
0.4
0.2
0.0
Queuing Delay
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
0.95
0.98
Utilization


theory
simulation
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Queuing Delay
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
0.95
0.98
Utilization