

# 1 Delay and Little's Law (Level 2)

## 1.1 Introduction

Delay is another important measure of quality of a network, very relevant for real-time applications. The application processes concern over different types of delay - connection establishment delay, session response delay, end-to-end packet delay, jitter, etc. In this experiment, we will review the most basic and fundamental measure of delay, known as end-to-end packet delay in the network. The **end-to-end packet delay** denotes the sojourn time of a packet in the network and is computed as follows. Let  $a_i$  and  $d_i$  denote the time of arrival of packet  $i$  into the network (into the transport layer at the source node) and time of departure of the packet  $i$  from the network (from the transport layer at the destination node), respectively. Then, the sojourn time of the packet  $i$  is computed as  $(d_i - a_i)$  seconds. A useful measure of delay of a flow is the average end-to-end delay of all the packets in the flow, and is computed as

$$\text{average packet delay} = \frac{1}{N} \sum_{i=1}^N (d_i - a_i) \text{ secs}$$

where,  $N$  is the count of packets in the flow.

A packet may encounter delay at different layers (and nodes) in the network. The transport layer at the end hosts may delay packets to control flow rate and congestion in the network. At the network layer (at the end hosts and at the intermediate routers), the packets may be delayed due to queues in the buffers. In every link (along the route), the packets see channel access delay and switching/forwarding delay at the data link layer, and packet transmission delay and propagation delay at the physical layer. In addition, the packets may encounter processing delay (due to hardware restrictions). It is a common practice to group the various components of the delay under the following four categories: **queueing delay** (caused due to congestion in the network), **transmission delay** (caused due to channel access and transmission over the channel), **propagation delay** and **processing delay**. We will assume zero processing delay and define packet delay as

$$\text{end to end packet delay} = \text{queueing delay} + \text{transmission delay} + \text{propagation delay}$$

We would like to note that, in many scenarios, the propagation delay and transmission delay are relatively constant in comparison with the queueing delay. This permits us (including applications and algorithms) to use packet delay to estimate congestion (indicated by the queueing delay) in the network.

### 1.1.1 Little's Law

The average end-to-end packet delay in the network is related to the average number of packets in the network. **Little's law** states that the average number of packets in the network is equal to the average arrival rate of packets into the network multiplied by the average end-to-end delay in the network, i.e.,

$$\begin{aligned} &\text{average number of packets in the network} \\ &= \text{average arrival rate into the network} \times \text{average end to end delay in the network} \end{aligned}$$

Likewise, the average queuing delay in a buffer is also related to the average number of packets in the queue via Little's law.

$$\text{average number of packets in queue} = \text{average arrival rate into the queue} \times \text{average delay in the queue}$$

The following figure illustrates the basic idea behind Little's law. In Figure 1-1a, we plot the arrival process  $a(t)$  (thick black line) and the departure process  $d(t)$  (thick red line) of a queue as a function of time. We have also indicated the time of arrivals ( $a_i$ ) and time of departures ( $d_i$ ) of the four packets in Figure 1-1a. In Figure 1-1b, we plot the queue process  $q(t) = a(t) - d(t)$  as a function of time, and in Figure 1-1c, we plot the waiting time ( $d_i - a_i$ ) of the four packets in the network. From the figures, we can note that the area under the queue process is the same as the sum of the waiting time of the four packets. Now, the average number of packets in the queue ( $\frac{14}{10}$ ), if we consider a duration of ten seconds for the experiment) is equal to the product of the average arrival rate of packets ( $\frac{4}{10}$ ) and the average delay in the queue ( $\frac{14}{4}$ ).

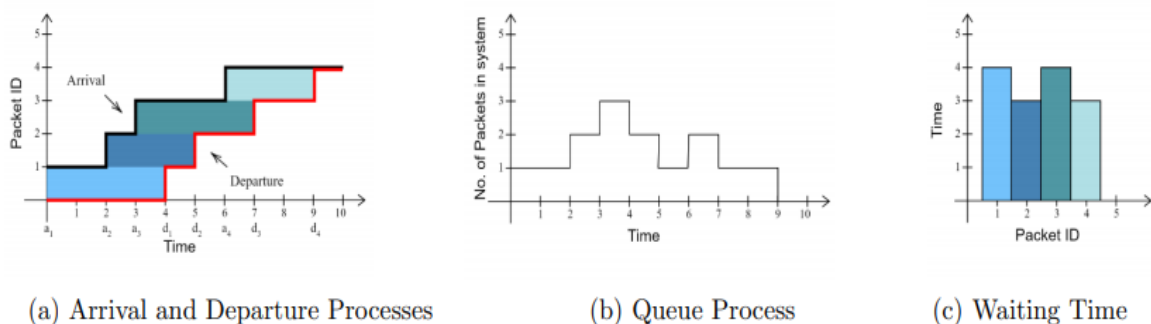


Figure 1-1: Illustration of Little's law in a queue.

In Experiment 3 (Throughput and Bottleneck Server Analysis), we noted that bottleneck server analysis can provide tremendous insights on the flow and network performance. Using M/G/1 analysis of the bottleneck server and Little's law, we can analyze queuing delay at the

bottleneck server and predict end-to-end packet delay as well (assuming constant transmission times and propagation delays).

## 1.2 NetSim Simulation Setup

Open NetSim and click on **Experiments> Internetworks> Network Performance> Delay and Littles Law** then click on the tile in the middle panel to load the example as shown below in Figure 1-2.

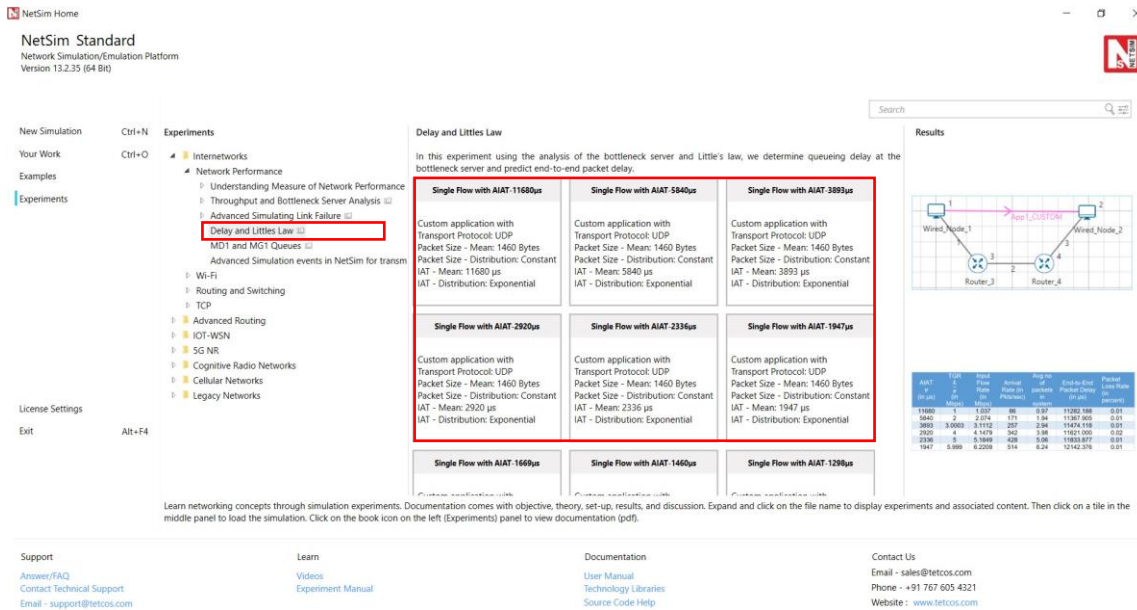


Figure 1-2: List of scenarios for the example of Delay and Littles Law

## 1.3 Part-1: A Single Flow Scenario

We will study a simple network setup with a single flow illustrated in Figure 1-3 to review end to end packet delay in a network as a function of network traffic. An application process at Wired\_Node\_1 seeks to transfer data to an application process at Wired\_Node\_2. We will consider a custom traffic generation process (at the application) that generates data packets of constant length (say, L bits) with i.i.d. inter-arrival times (say, with average inter-arrival time  $\nu$  seconds). The application traffic generation rate in this setup is  $\frac{L}{\nu}$  bits per second. We prefer to minimize communication overheads (including delay at the transport layer) and hence, will use UDP for data transfer between the application processes.

In this setup, we will vary the traffic generation rate ( $\frac{L}{\nu}$ ) by varying the average inter-arrival time ( $\nu$ ), and review the average queue at the different links, average queueing delay at the different links and end-to-end packet delay.

### 1.3.1 Procedure

We will simulate the network setup illustrated in Figure 1-3 with the configuration parameters listed in detail in Table 1-1 to study the single flow scenario.

NetSim UI displays the configuration file corresponding to this experiment as shown below:

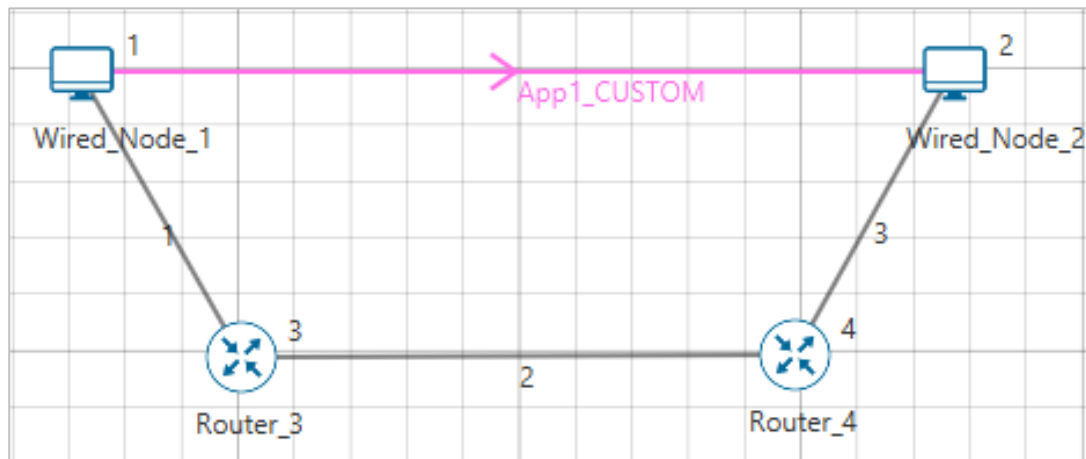


Figure 1-3: Network set up for studying a single flow

The following set of procedures were done to generate this sample:

**Step 1:** Drop two wired nodes and two routers onto the simulation environment. The wired nodes and the routers are connected with wired links as shown in (See Figure 1-3).

**Step 2:** Click the **Application** icon to configure a custom application between the two wired nodes. In the **Application** configuration dialog box (see Figure 1-4), select **Application Type** as CUSTOM, **Source ID** as 1 (to indicate Wired\_Node\_1), **Destination ID** as 2 (to indicate Wired\_Node\_2) and **Transport Protocol** as UDP. In the PACKET SIZE tab, select **Distribution** as CONSTANT and **Value** as 1460 bytes. In the INTER ARRIVAL TIME tab, select **Distribution** as EXPONENTIAL and **Mean** as 11680 microseconds.

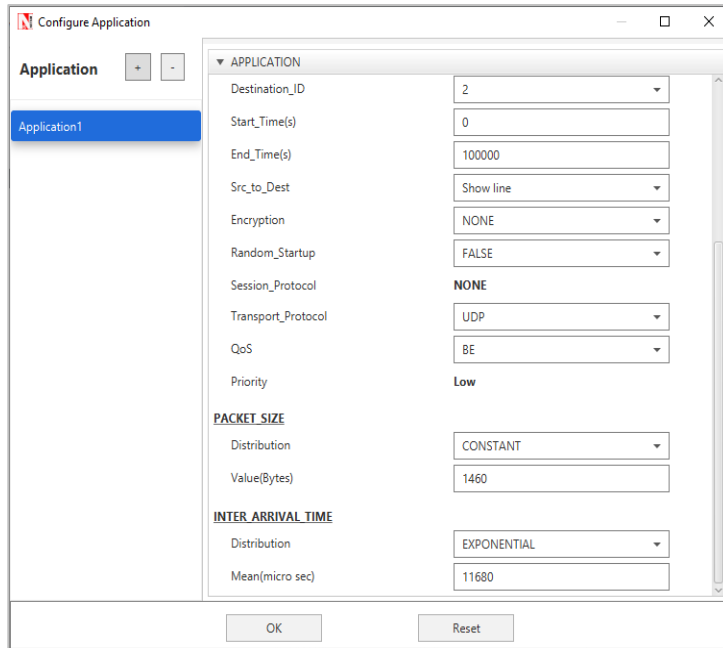


Figure 1-4: Application configuration dialog box

**Step 3:** The properties of the wired nodes are left to the default values.

**Step 4:** Right-click the link ID (of a wired link) and select **Properties** to access the link’s properties dialog box (see Figure 1-5). Set **Max Uplink Speed** and **Max Downlink Speed** to 10 Mbps for link 2 (the backbone link connecting the routers) and 1000 Mbps for links 1 and 3 (the access link connecting the Wired\_Nodes and the routers).

Set **Uplink BER** and **Downlink BER** as 0 for links 1, 2 and 3. Set **Uplink\_Propagation Delay** and **Downlink\_Propagation Delay** as 0 microseconds for the two-access links 1 and 3 and 10 milliseconds for the backbone link 2.

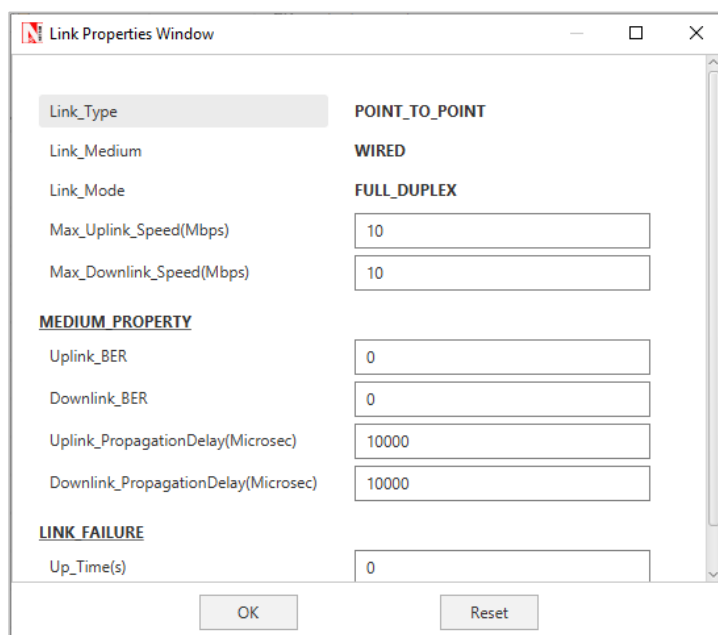


Figure 1-5: Link\_ID\_2 Properties dialog box

**Step 5:** Right-click **Router 3** icon and select **Properties** to access the link's properties dialog box (see Figure 1-6). In the **INTERFACE 2 (WAN)** tab, select the **NETWORK LAYER** properties, set **Buffer size (MB)** to **8**.

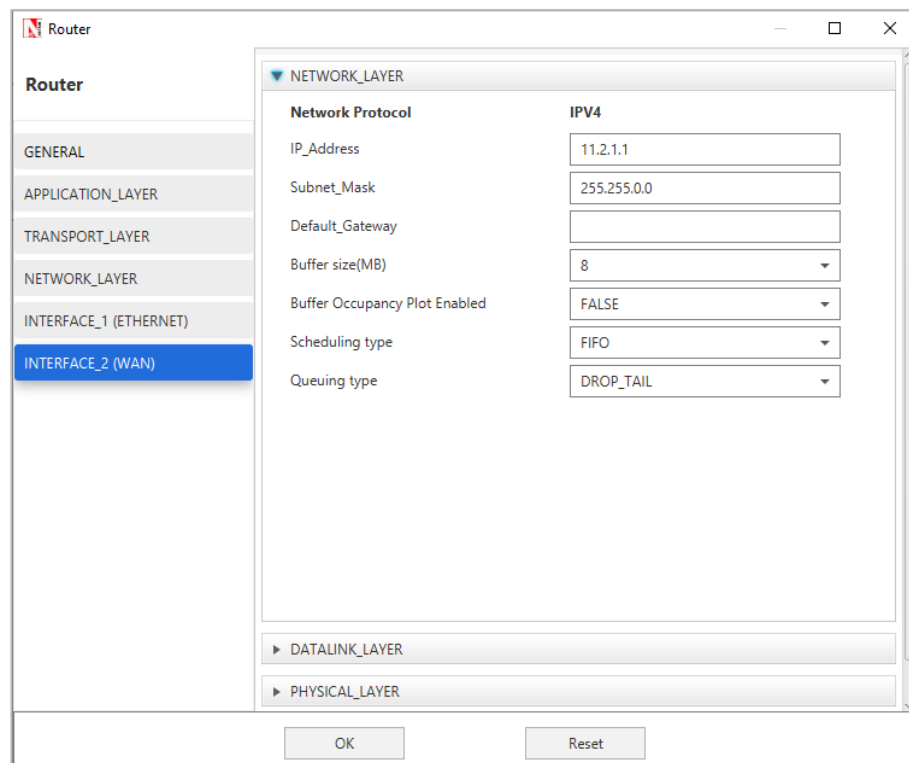


Figure 1-6: Router Properties dialog box

**Step 6: Enable Plots and Packet Trace** check box. Packet Trace can be used for packet level analysis.

**Step 7:** Click on **Run** icon to access the Run Simulation dialog box (see Figure 1-7) and set the **Simulation Time** to 100 seconds in the **Simulation Configuration** tab. Now, run the simulation.

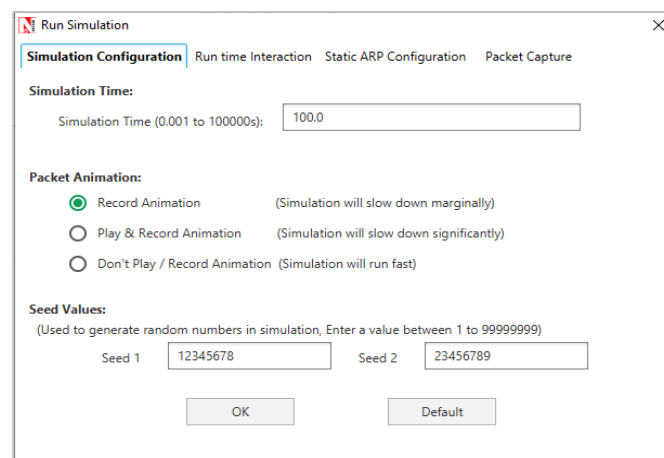


Figure 1-7: Run Simulation dialog box

**Step 8:** Now, repeat the simulation with different average inter-arrival times (such as 5840  $\mu$ s, 3893  $\mu$ s, 2920  $\mu$ s, 2336  $\mu$ s and so on). We vary the input flow rate by varying the average inter-arrival time. This should permit us to identify the bottleneck link and the maximum achievable throughput.

The detailed list of network configuration parameters is presented in (See Table 1-1).

Parameter	Value
<b>LINK PARAMETERS</b>	
Wired Link Speed (access link)	1000 Mbps
Wired Link Speed (backbone link)	10 Mbps
Wired Link BER	0
Wired Link Propagation Delay (access link)	0
Wired Link Propagation Delay (backbone link)	10 milliseconds
<b>APPLICATION PARAMETERS</b>	
Application	Custom
Source ID	1
Destination ID	2
Transport Protocol	UDP
Packet Size – Value	1460 bytes
Packet Size – Distribution	Constant
Inter Arrival Time – Mean	AIAT ( $\mu$ s) Table 1-2
Inter Arrival Time – Distribution	Exponential
<b>ROUTER PARAMETERS</b>	
Buffer Size	8
<b>MISCELLANEOUS</b>	
Simulation Time	100 Sec
Packet Trace	Enabled
Plots	Enabled

Table 1-1: Detailed Network Parameters

### 1.3.2 Performance Measure

In Table 1-2 and Table 1-3, we report the flow average inter-arrival time  $v$  and the corresponding application traffic generation rate, input flow rate (at the physical layer), average queue and delay of packets in the network and in the buffers, and packet loss rate.

Given the average inter-arrival time  $v$  and the application payload size  $L$  bits (here,  $1460 \times 8 = 11680$  bits), we have,

$$\text{Traffic generation rate} = \frac{L}{v} = \frac{11680}{v} \text{ bps}$$

$$\text{input flow rate} = \frac{11680 + 54 \times 8}{v} = \frac{12112}{v} \text{ bps}$$

where the packet overheads of 54 bytes is computed as  $54 = 8(\text{UDP header}) + 20(\text{IP header}) + 26(\text{MAC} + \text{PHY header})$  bytes.

Let  $Q_l(u)$  as denote the instantaneous queue at link  $l$  at time  $u$ . Then, the average queue at link  $l$  is computed as

$$\text{average queue at link } l = \frac{1}{T} \int_0^T Q_l(u) \, du \text{ bits}$$

where,  $T$  is the simulation time. And, let  $N(u)$  denote the instantaneous number of packets in the network at time  $u$ . Then, the average number of packets in the network is computed as

$$\text{average number of packet in the network} = \frac{1}{T} \int_0^T N(u) \, du \text{ bits}$$

Let  $a_{i,l}$  and  $d_{i,l}$  denote the time of arrival of a packet  $i$  into the link  $l$  (the corresponding router) and the time of departure of the packet  $i$  from the link  $l$  (the corresponding router), respectively. Then, the average queueing delay at the link  $l$  (the corresponding router) is computed as

$$\text{average queueing delay at link } l = \frac{1}{N} \sum_{i=1}^N (d_{i,l} - a_{i,l})$$

where  $N$  is the count of packets in the flow. Let  $a_i$  and  $d_i$  denote the time of arrival of a packet  $i$  into the network (into the transport layer at the source node) and time of departure of the packet  $i$  from the network (from the transport layer at the destination node), respectively. Then, the end-to-end delay of the packet  $i$  is computed as  $(d_i - a_i)$  seconds, and the average end to end delay of the packets in the flow is computed as

$$\text{average end to end packet delay} = \frac{1}{N} \sum_{i=1}^N (d_i - a_i)$$

### 1.3.2.1 Average Queue Computation from Packet Trace

- Open Packet Trace file using the **Open Packet Trace** option available in the Simulation Results window.
- In the Packet Trace, filter the data packets using the column **CONTROL PACKET TYPE/APP NAME** and the option **App1 CUSTOM** (see Figure 1-8).



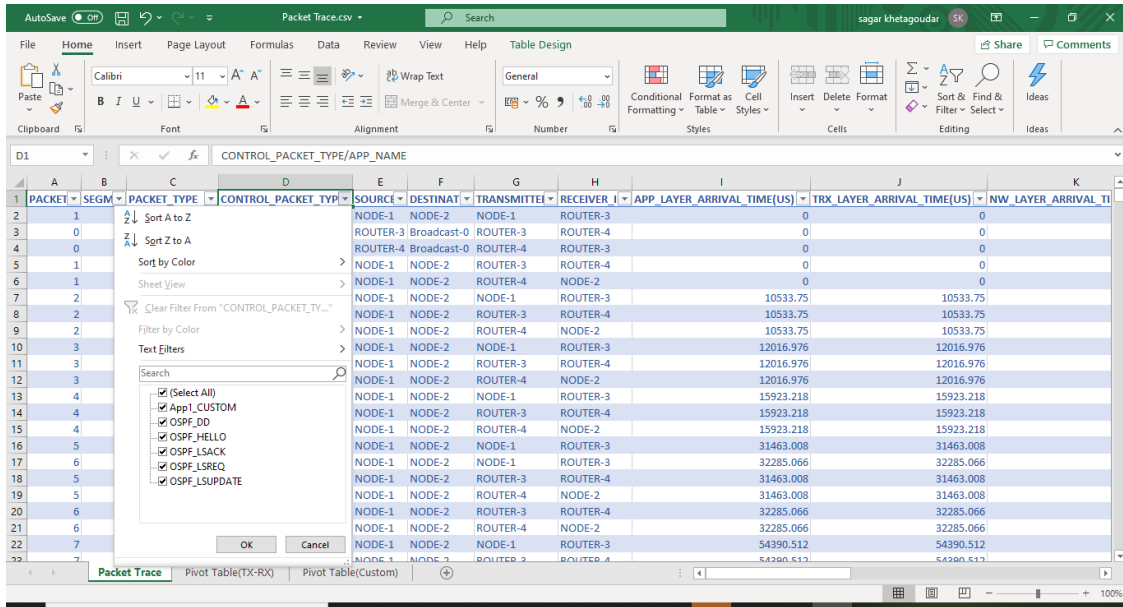


Figure 1-8: Filter the data packets in Packet Tracer by selecting App1 CUSTOM.

- Now, to compute the average queue in Link 2, we will select **TRANSMITTER\_ID** as **ROUTER-3** and **RECEIVER\_ID** as **ROUTER-4**. This filters all the successful packets from Router 3 to Router 4.
- The columns **NW\_LAYER\_ARRIVAL\_TIME(US)** and **PHY\_LAYER\_ARRIVAL\_TIME(US)** correspond to the arrival time and departure time of the packets in the buffer at Link 2, respectively (see Figure 1-9).
- You may now count the number of packets arrivals (departures) into (from) the buffer upto time  $t$  using the **NW\_LAYER\_ARRIVAL\_TIME(US)** (**PHY\_LAYER\_ARRIVAL\_TIME(US)**) column. The difference between the number of arrivals and the number of departures gives us the number of packets in the queue at any time.

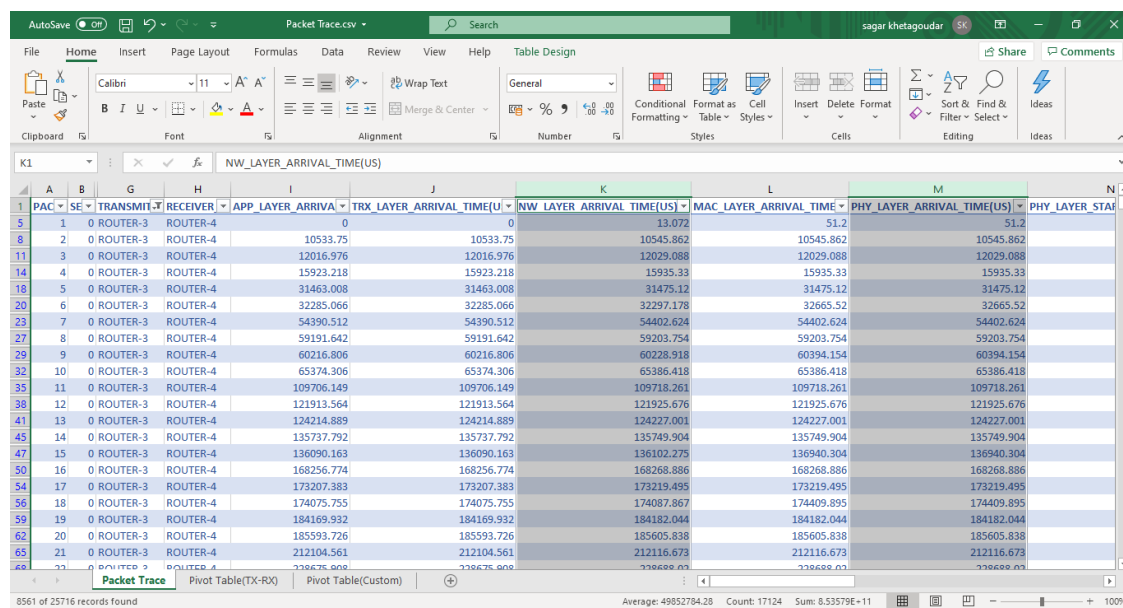


Figure 1-9: Packet arrival and departure times in the link buffer

- Calculate the average queue by taking the mean of the number of packets in queue at every time interval during the simulation.
- The difference between the PHY LAYER ARRIVAL TIME(US) and the NW LAYER ARRIVAL TIME(US) will give us the delay of a packet in the link (see Figure 1-10).

$$\text{Queuing Delay} = \text{PHY LAYER ARRIVAL TIME(US)} - \text{NW LAYER ARRIVAL TIME(US)}$$

	I	J	K	L	M	N
1	APP_LAYER_ARRIVAL_TIME(US)	TRX_LAYER_ARRIVAL_TIME(US)	NW_LAYER_ARRIVAL_TIME(US)	MAC_LAYER_ARRIVAL_TIME(US)	PHY_LAYER_ARRIVAL_TIME(US)	Queuing Delay
7	0	0	13.072	51.2	51.2	38.128
10	1053.375	1053.375	1065.487	1241.6	1241.6	178.213
14	1201.698	1201.698	1213.81	2432	2432	1218.19
16	1592.322	1592.322	1604.434	3622.4	3622.4	2017.966
21	3146.301	3146.301	3158.413	4812.8	4812.8	1654.387
24	3228.507	3228.507	3240.619	6003.2	6003.2	2762.581
26	5439.051	5439.051	5451.163	7193.6	7193.6	1742.437
28	5919.164	5919.164	5931.276	8384	8384	2452.724
30	6021.681	6021.681	6033.793	9574.4	9574.4	3540.607
33	6537.431	6537.431	6549.543	10764.8	10764.8	4215.257
37	10970.615	10970.615	10982.727	11955.2	11955.2	972.473
41	12191.356	12191.356	12203.468	13145.6	13145.6	942.132
43	12421.489	12421.489	12433.601	14336	14336	1902.399
45	13573.779	13573.779	13585.891	15526.4	15526.4	1940.509
50	13609.016	13609.016	13621.128	16716.8	16716.8	3095.672
54	16825.677	16825.677	16837.789	17907.2	17907.2	1069.411
56	17320.738	17320.738	17332.85	19097.6	19097.6	1764.75
59	17407.576	17407.576	17419.688	20288	20288	2868.312
61	18416.993	18416.993	18429.105	21478.4	21478.4	3049.295
64	18559.373	18559.373	18571.485	22668.8	22668.8	4097.315
68	21210.456	21210.456	21222.568	23859.2	23859.2	2636.632
70	22867.591	22867.591	22879.703	25049.6	25049.6	2169.897

Figure 1-10: Queuing Delay

- Now, calculate the average queuing delay by taking the mean of the queuing delay of all the packets (see Figure 1-10)

### 1.3.2.2 Network Delay Computation from Packet Trace

- Open Packet Trace file using the **Open Packet Trace** option available in the Simulation Results window
- In the Packet Trace, filter the data packets using the column **CONTROL PACKET TYPE/APP NAME** and the option **App1 CUSTOM** (see Figure 1-8).
- Now, we will select the **RECEIVER ID** as **NODE-2**. This filters all the successful packets in the network that reached Wired Node 2
- The columns **APP LAYER ARRIVAL TIME(US)** and **PHY LAYER END TIME(US)** correspond to the arrival time and departure time of the packets in the network respectively.
- You may now count the number of arrivals (departures) into (from) the network upto time t using the APP LAYER ARRIVAL TIME(US) (PHY LAYER END TIME(US)) column. The difference between the number of arrivals and the number of departures gives us the number of packets in the network at any time.
- Calculate the average number of packets in the network by taking the mean of the number of packets in network at every time interval during the simulation.
- Packet Delay at a per packet level can be calculated using the columns **Application Layer Arrival Time** and **Physical Layer End Time** in the packet trace as:

$$\text{End-to-End Delay} = \text{PHY LAYER END TIME(US)} - \text{APP LAYER ARRIVAL TIME(US)}$$

- Calculate the average end-to-end packet delay by taking the mean of the difference between Phy Layer End Time and App Layer Arrival Time columns.

**NOTE:** To calculate average number of packets in queue refer the experiment on *Throughput and Bottleneck Server Analysis*.

### 1.3.3 Results

In Table 1-2, we report the flow average inter-arrival time (AIAT) and the corresponding application traffic generation rate (TGR), input flow rate (at the physical layer), average number of packets in the system, end-to-end packet delay in the network and packet loss rate.

AIAT $\nu$ (in $\mu$ s)	TGR $\frac{L}{\nu}$ (in Mbps)	Input Flow Rate (in Mbps)	Arrival Rate (in Pkts/sec)	Avg no of packets in system	End-to-End Packet Delay (in $\mu$ s)	Packet Loss Rate (in percent)
11680	1	1.037	86	0.97	11282.188	0.01
5840	2	2.074	171	1.94	11367.905	0.01
3893	3.0003	3.1112	257	2.94	11474.118	0.01
2920	4	4.1479	342	3.98	11621.000	0.02
2336	5	5.1849	428	5.06	11833.877	0.01
1947	5.999	6.2209	514	6.24	12142.376	0.01
1669	6.9982	7.257	599	7.58	12664.759	0.01
1460	8	8.2959	685	9.48	13846.543	0.01
1298	8.9985	9.3313	770	13.73	17840.278	0.02
1284	9.0966	9.433	779	14.73	18917.465	0.02
1270	9.1969	9.537	787	15.98	20318.735	0.02
1256	9.2994	9.6433	796	17.74	22299.341	0.01
1243	9.3966	9.7442	805	20.31	25243.577	0.01
1229	9.5037	9.8552	814	25.77	31677.196	0.03
1217	9.5974	9.9523	822	35.06	42660.631	0.02
1204	9.701	10.0598	831	51.87	62466.981	0.06
1192	9.7987	10.1611	839	101.21	120958.109	0.268
1180	9.8983	10.2644	847	442.71	528771.961	1.152
1168	10	10.3699	856	856.98	1022677.359	2.105
1062	10.9981	11.4049	942	3876.87	4624821.867	11.011
973	12.0041	12.4481	1028	4588.84	5479885.160	18.541
898	13.0067	13.4878	1114	4859.68	5797795.877	24.758
834	14.0048	14.5228	1199	4998.91	5964568.493	30.100
779	14.9936	15.5481	1284	5081.93	6066291.390	34.756

Table 1-2: Packet arrival rate, average number of packets in the system, end-to-end delay and packet loss rate.

#### Calculation

Calculation done for AIAT 11680 $\mu$ s Sample:

$$\text{Arrival Rate} = \frac{1\text{sec}}{IAT} = \frac{1000000}{11680} = 86 \text{ pkts/Sec}$$

$$\text{Packet loss} = \frac{\text{Packet generated} - \text{packet received}}{\text{Packet generated}} = \frac{8562 - 8561}{8562} \times 100 = 0.01\%$$

$$\text{average number of packets in the system} = \text{Arrival rate} \times \text{Dealy} \times (1 - \text{Packet loss})$$

$$\text{Packet loss} = \frac{\text{packet loss}(\%)}{100} = \frac{0.01}{100} = 0.0001$$

End to End packet delay in  $\mu\text{s}$ , Convert  $\mu\text{s}$  into sec

$$= 11282.188 \mu\text{s} = 0.011282188 \text{ Sec}$$

Therefore,

$$\text{average number of packets in the system} = \text{Arrival rate} \times \text{Dealy} \times (1 - \text{Packet loss})$$

$$= 86 \times 0.011282188 \times (1 - 0.0001)$$

$$= 86 \times 0.011282188 \times 0.9999$$

$$= 0.97$$

We can infer the following from Table 1-2.

- The average end-to-end packet delay (between the source and the destination) is bounded below by the sum of the packet transmission durations and the propagation delays of the constituent links ( $2 \times 12 + 1211 + 10000$  microseconds).
- As the input flow rate increases, the packet delay increases as well (due to congestion and queueing in the intermediate routers). As the input flow rate matches or exceeds the bottleneck link capacity, the end-to-end packet delay increases unbounded (limited by the buffer size).
- The average number of packets in the network can be found to be equal to the product of the average end-to-end packet delay and the average input flow rate into the network. This is a validation of the Little’s law. In cases where the packet loss rate is positive, the arrival rate is to be multiplied by  $(1 - \text{packet loss rate})$ .

In Table 1-3, we report the average queue and average queueing delay at the intermediate routers (Wired Node 1, Router 3 and Router 4) and the average end-to-end packet delay as a function of the input flow rate.

Input Flow Rate (in Mbps)	Arrival Rate (in Pkts/sec)	Avg no of packets in Queue			Average Queueing Delay (in $\mu\text{s}$ )			End-to-End Packet Delay (in $\mu\text{s}$ )
		Node 1	Router 3	Router 4	Node 1	Router 3	Router 4	

1.037	86	0	0	0	0.008	67.55	0	11282.188
2.074	171	0	0	0	0.015	153.26	0	11367.905
3.1112	257	0	0.08	0	0.021	259.47	0	11474.118
4.1479	342	0	0.13	0	0.029	406.35	0	11621.00
5.1849	428	0	0.26	0	0.035	619.21	0	11833.87
6.2209	514	0	0.45	0	0.046	927.70	0	12142.376
7.257	599	0	0.92	0	0.054	1450.08	0	12664.759
8.2959	685	0	1.82	0	0.062	2631.85	0	13846.543
9.3313	770	0	5.14	0	0.070	6625.58	0	17840.278
9.433	779	0	6.86	0	0.070	7702.77	0	18917.465
9.537	787	0	7.98	0	0.071	9104.04	0	20318.73
9.6433	796	0	7.82	0	0.071	11084.64	0	22299.341
9.7442	805	0	10.96	0	0.073	14028.88	0	25243.577
9.8552	814	0	16.12	0	0.073	20462.49	0	31677.196
9.9523	822	0	25.73	0	0.073	31445.93	0	42660.631
10.0598	831	0	42.86	0	0.074	51252.28	0	62466.981
10.1611	839	0	91.08	0	0.074	109743.41	0	120958.109
10.2644	847	0	434	0	0.076	517557.26	0	528771.961
10.3699	856	0	849.15	0	0.077	1011462.6	0	1022677.359
11.4049	942	0	3873.87	0	0.085	4613607.1	0	4624821.867
12.4481	1028	0	4593.12	0	0.093	5468670.4	0	5479885.160
13.4878	1114	0	4859.15	0	0.099	5786581.1	0	5797795.877
14.5228	1199	0	5000.13	0	0.106	5953353.8	0	5964568.493
15.5481	1284	0	5084.63	0	0.113	6055076.7	0	6066291.390

Table 1-3: Average queue and average queueing delay in the intermediate buffers and end-to-end packet delay

We can infer the following from Table 1-3.

- There is queue buildup as well as queueing delay at Router\_3 (Link 2) as the input flow rate increases. Clearly, link 2 is the bottleneck link where the packets see large queueing delay.
- As the input flow rate matches or exceeds the bottleneck link capacity, the average queueing delay at the (bottleneck) server increases unbounded. Here, we note that the maximum queueing delay is limited by the buffer size (8 MB) and link capacity (10 Mbps), and an upper bounded is  $8 \times 1024 \times 1024 \times 8 \times 10^7 = 6.7$  seconds.
- The average number of packets in a queue can be found to be equal to the product of the average queueing delay and the average input flow rate into the network. This is again a validation of the Little's law. In cases where the packet loss rate is positive, the arrival rate is to be multiplied by  $(1 - \text{packet loss rate})$ .
- The average end-to-end packet delay can be found to be equal to the sum of the packet transmission delays (12.112 $\mu$ s (link 1), 1211 $\mu$ s (link 2), 12.112  $\mu$ s (link3)), propagation delay (10000  $\mu$ s) and the average queueing delay in the three links.

For the sake of the readers, we have made the following plots for clarity. In Figure 1-11, we plot the average end-to-end packet delay as a function of the traffic generation rate. We note

that the average packet delay increases unbounded as the traffic generation rate matches or exceeds the bottleneck link capacity.

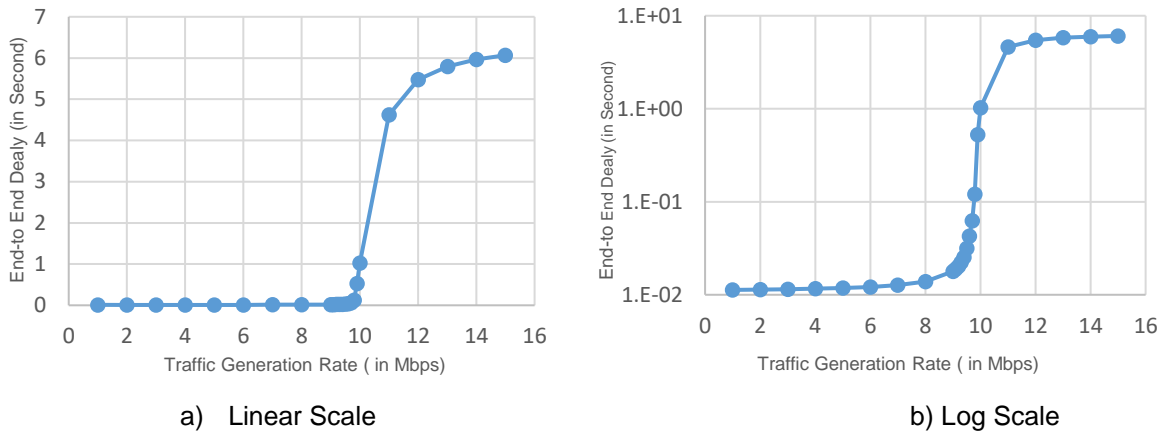


Figure 1-11: Average end-to-end packet delay as a function of the traffic generation rate.

In Figure 1-12, we plot the queueing delay experienced by few packets at the buffers of Links 1 and 2 for two different input flow rates. We note that the packet delay is a stochastic process and is a function of the input flow rate and the link capacity as well.

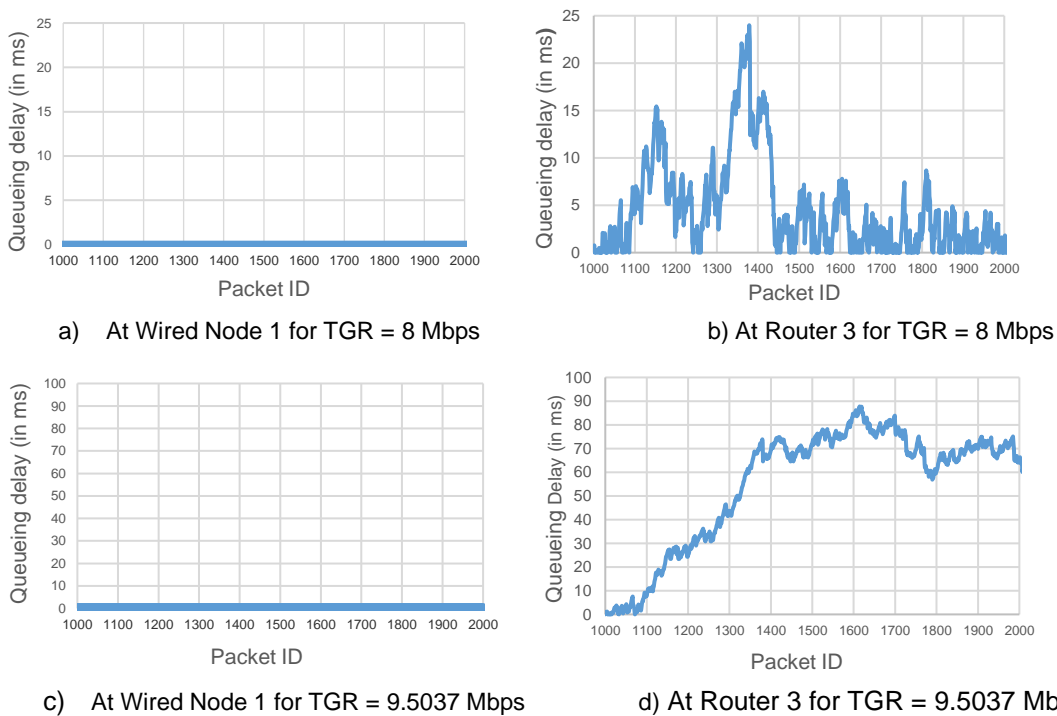


Figure 1-12: Queueing Delay of packets at Wired\_Node\_1 (Link 1) and Router\_3 (Link 2) for two different traffic generation rates

### 1.3.3.1 Bottleneck Server Analysis as M/G/1 Queue

Suppose that the application packet inter-arrival time is i.i.d. with exponential distribution. From the M/G/1 queue analysis (in fact, M/D/1 queue analysis), we know that the average queueing delay at the link buffer (assuming large buffer size) must be.

$$\text{average queueing delay} = \frac{1}{\mu} + \frac{1}{2\mu} \frac{\rho}{1-\rho} = \lambda \times \text{average queue}$$

where  $\rho$  is the offered load to the link,  $\lambda$  is the input flow rate in packet arrivals per second and  $\mu$  is the service rate of the link in packets served per second. Notice that the average queueing delay increases unboundedly as  $\rho \rightarrow 1$ .

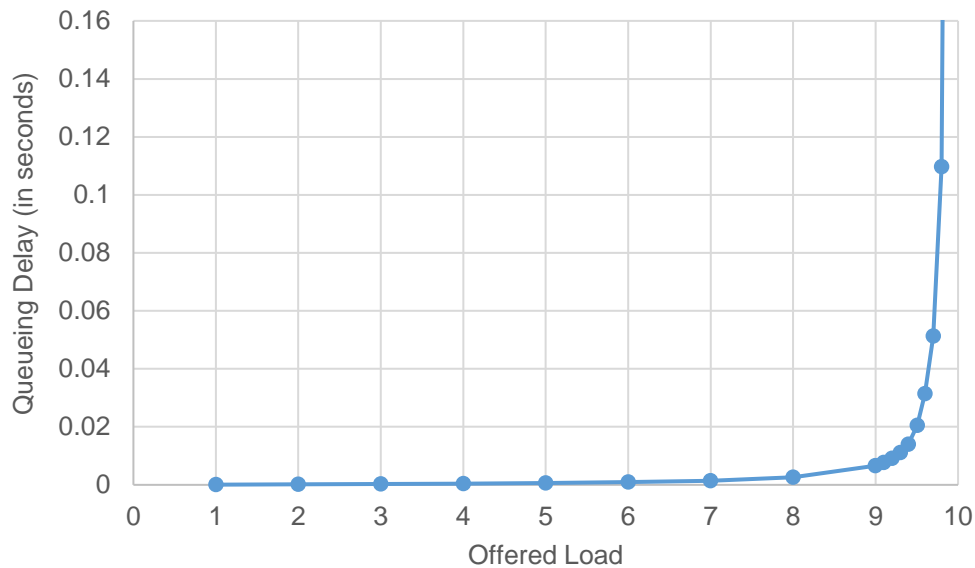


Figure 1-13: Average queueing delay (in seconds) at the bottleneck link 2 (at Router 3) Average queueing delay (in seconds) at the bottleneck link 2 (at Router 3) as a function of the offered load.

In Figure 1-13, we plot the average queueing delay (from simulation) and from (1) (from the bottleneck analysis) as a function of offered load  $\rho$ . Clearly, the bottleneck link analysis predicts the average queue (from simulation) very well. Also, we note from (1) that the network performance depends on  $\lambda$  and  $\mu$  as  $\frac{\lambda}{\mu} = \rho$  only.