Due Date: December 3, 2024

Motivation:

In a data network, Kleinrock's Independence Approximation is a powerful tool to analyze the network. However, this provides only an approximation owing to the assumption that the inter-arrival and service times are independent on each transmission link in the network so that an M/M/1 queuing model can be adopted for each link. In reality, the inter-arrival and service times are strongly correlated on all links except the entry link. This approximation only works well under certain conditions. This project explores how well the Kleinrock's approximation models an actual system with a single source of data in terms of the average delay per packet and the average number of packets in the system.

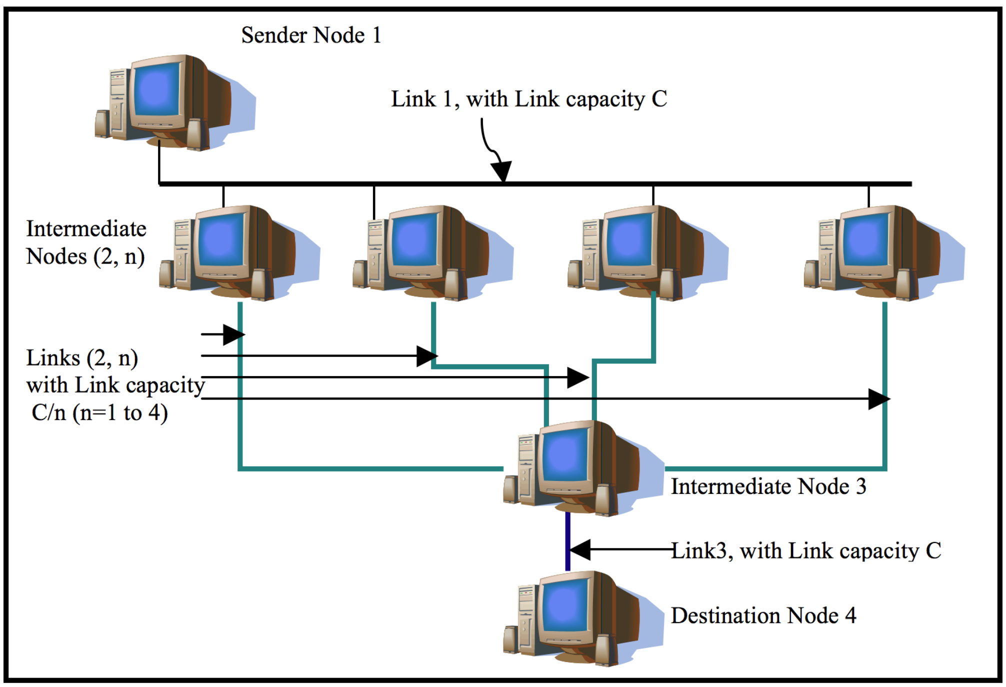

Figure 1: System Setup

Specification:

Consider a system in which a sender computer transmits packets to a destination computer via a network as shown in Figure 1. The sender sends packets at the rate of λ packets/sec. Each packet can reach the destination via one of possible alternate routes. The sender transmits the packets on a shared medium, link 1, with capacity C. Each packet is independently routed with probability p_n to one of the intermediate forwarding nodes $(2, n)$. From here, the packets are transmitted over dedicated point-to-point links each of capacity C/n to intermediate node 3. Finally, the packets are transmitted over link 3 of capacity C, and arrive at the destination node.

Now, let's analyze the above system from a queuing perspective.

For the purpose of queuing analysis, the computers can be modeled as queues representing the packet buffers they contain, and the links can be modeled as servers (the service provided in this case is the transmission of packets). The queuing model for the system above is shown in Figure 2 below.

Packets arrive at the system entry (transmitted by sender) following a Poisson process with an arrival rate of λ. Packet lengths are exponentially distributed, i.e., packet service time is exponentially distributed. At the output of server 1 (with link capacity C), each packet is independently routed with probability p_n to one of the intermediate queues. (We will analyze the system for different number of intermediate queues between 1 and n.) If this statistical splitting of packets is done with equal probabilities, the arrival rate at the input of each intermediate queue would be $\frac{\lambda}{n}$. From here, packets are transmitted over their respective outgoing servers, each of link capacity $\frac{C}{n}$. Packets then merge before entering queue 3. The merging will produce a stream of packets with arrival rate λ at the input of queue 3. The packets are then transmitted over server 3 (with link capacity C), after which they exit the system (reach the destination node). Assume that a packet is immediately served if it finds an empty server and that the propagation and processing delays are negligible.

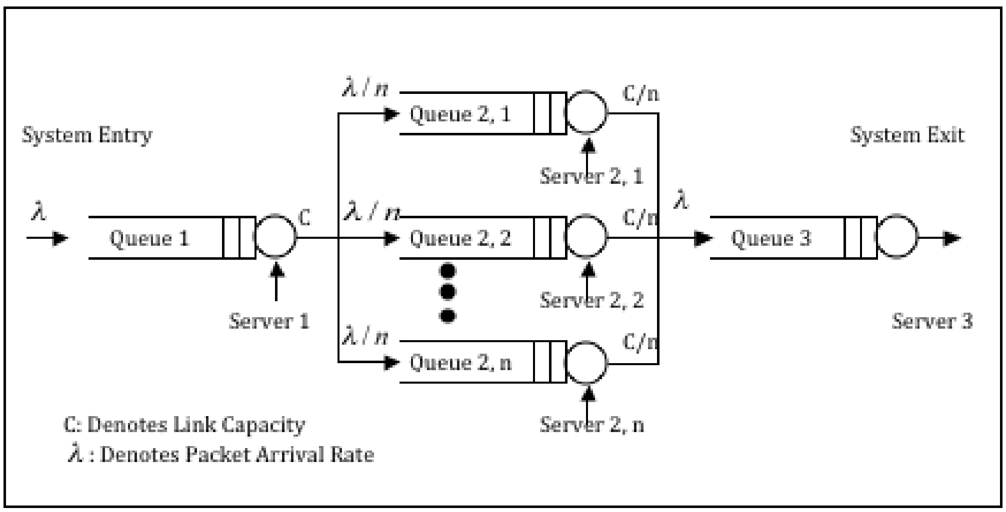

Figure 2: Queuing Model of the System

Tasks:

In this project, you will simulate the queuing system described above for $n = 1, 2, 3, 4$. The routing probabilities for each case are given as follows:

Case	p_1	p_2	p_3	p_4
$n = 1$	1	0	0	0
$n = 2$	0.5	0.5	0	0
$n = 3$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	0
$n = 4$	0.25	0.25	0.25	0.25

The packet arrival rate λ will range from 50 packets/sec to 1200 packets/sec with increments of 50. Assume C=10 Mbits/sec and the average packet length is 1000 bytes. To generate reasonable results, be sure the system reaches the steady state. (A safe bet would be to run the system for 50000 packet transmissions or more.) You can use any programming language to write the simulator.

Consider a queuing subsystem to be composed of a queue attached to a server connected to an outgoing link as shown in Figure 3.

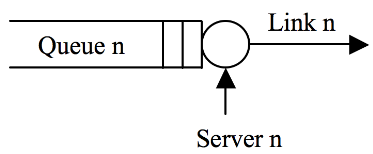

Figure 3: Queuing Subsystem at each Node

In your simulation, keep track of the following quantities:

1. Average packet delay through each queuing subsystem.
2. Average number of packets in each queuing subsystem

Plot the simulated averages as well as the theoretical average values calculated using Kleinrock's Independence Approximation as a function of the arrival rate λ.

Deliverables:

A single PDF file containing the items below will be submitted on Carmen. The two justification descriptions should be substantiated in detail through theoretical arguments. Make sure to include your full name in the project report.

1. **Chart Type A: Quantitative Charts**
   - For each $n = 1, 2, 3, 4$, plot the simulation results and theoretical values for the average packet delay through each queuing subsystem as a function of λ. (One chart for subsystem 1, One chart representative of one of the subsystems $(2, n)$, and one chart for subsystem 3.)
   - For each $n = 1, 2, 3, 4$, plot the simulation results and theoretical values for the average number of packets N in each queuing subsystem as a function of λ. (One chart for subsystem 1, One chart representative of one of the subsystems $(2, n)$, and one chart for subsystem 3.)
   - For each $n = 1, 2, 3, 4$, the charts described above may be grouped together into a single graph as shown in the sample graph of Figure 4.
   - For each case $n = 1, 2, 3, 4$, is the deviation in theoretical and simulated value of delay and N for subsystem $(2, 1)$ and 3 more than or less than deviation observed for subsystem 1? Give justifications for your answer.
2. **Chart Type B: Comparative Charts**
   - For each subsystem 1, $(2, 1)$ and 3, plot the difference between simulation results and theoretical values for the average packet delay as a function of λ, for $n = 1, 2, 3, 4$.
   - For each subsystem 1, $(2, 1)$ and 3, plot the difference between simulation results and theoretical values for the average number of packets N as a function of λ, for $n = 1, 2, 3, 4$.
   - For each subsystem, the charts described above can be grouped together into a single graph as shown in the sample graph of Figure 5.

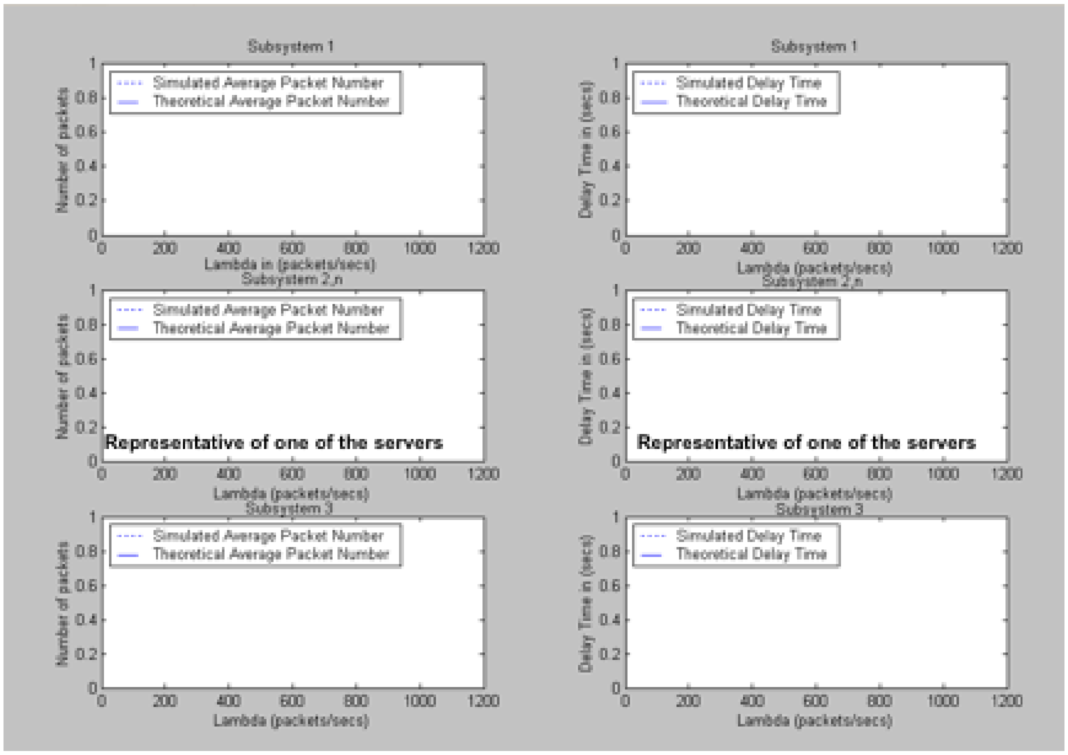

Figure 4: Sample Format (one such graph for each case $n = 1, 2, 3, 4$)

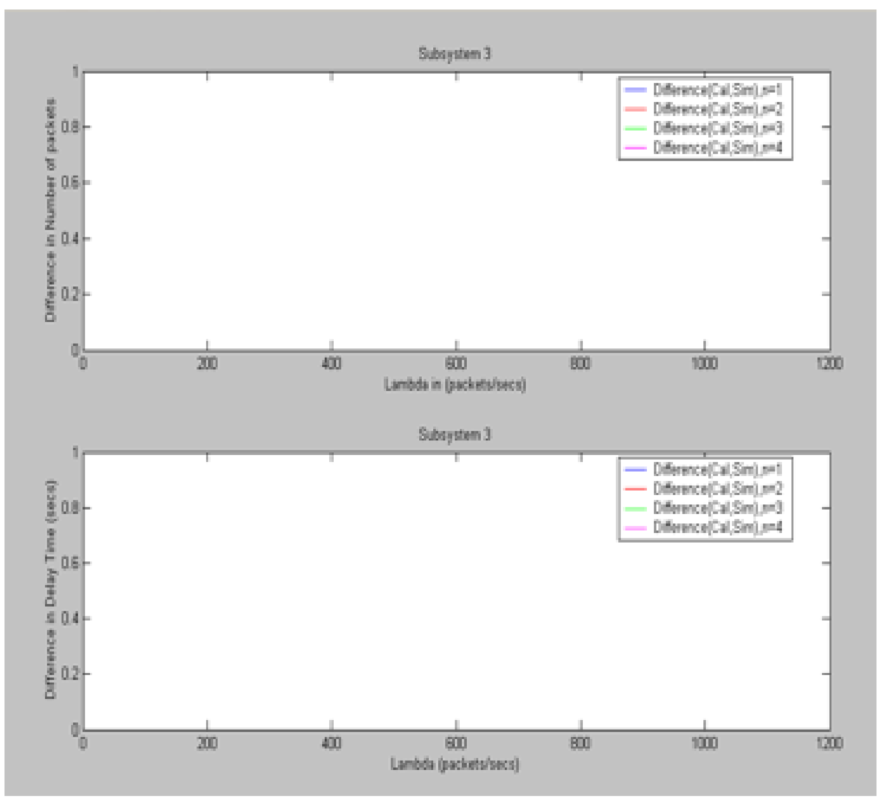

Figure 5: Sample Format (one such graph for each case $n = 1, 2, 3, 4$)

- For each subsystem, compare the deviation in theoretical and simulated values of delay and N observed for $n = 1, 2, 3, 4$. Give justifications for your answer.

3. **Simulation source code**

Important Notes:

- This is **NOT** a group project. You are encouraged to discuss your methods with your peers, but sharing of codes, code segments, and results is not allowed.
- The project will be counted towards 25 percent of your final grade.
- Each day after the submission deadline will lead to an automatic deduction of 20 points out of a possible 100 points.