**ECE 358: Computer Networks**

**Project 1: M/D/1 and M/D/1/K Queue Simulation**

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# Question 1

**Explain your program in detail. Should there be a need, draw diagrams to show your program structure. Explain how you compute the performance metrics.**

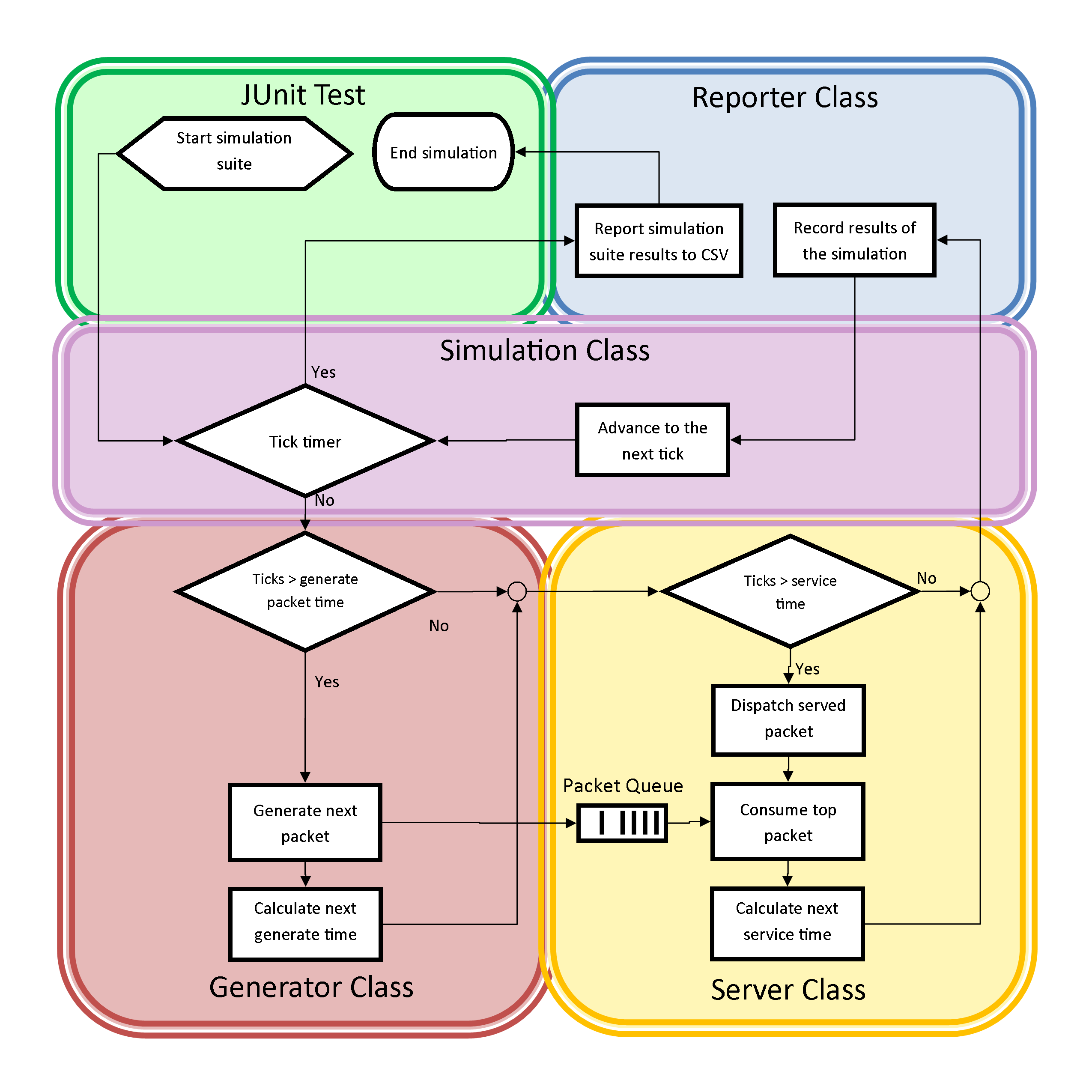


Figure 1 Diagram of simulation structure and flow

## Junit Tests

We created the design of the simulation (seen above in Figure 1) with the idea that simulations would be ran multiple times with different variables. To meet this requirement we designed several JUnit tests that would setup the simulation parameters, run the simulation, record the results, change the parameters as required, and repeat. The additional value of using JUnit was the ability to create a series of tests to help validate the simulation results. If one of the Junit tests failed, it might indicate that a code regression has occurred.

## Simulator Class

The core of the project is the Simulator class, which controls the overall flow of the simulation. When a JUnit test begins a simulation, it provides setup parameters to run the simulation. The Simulator class contains the main program loop that updates the Generator, Server, and Reporter class with the current time tick until the current tick is greater than the total simulation time parameter. After the simulation is complete, control is returned to the Junit test, which will record the previous results and will setup the next simulation.

## Generator Class

The Generator class encapsulates the packet arrival process to generate packets at a rate of packets per second. By specification, a packet arrives at a random interval, which we model by an exponential random variable U. The random variable U means that a packet may arrive earlier or later than every seconds, however over a long period of time will average out to packets per second. Each time a new packet is generated the Generator adds the packet to the queue and calculates the time in ticks until next packet arrives. The Generator will remain idle until the next packet arrival tick occurs when a new packet is generated and the next arrival time is calculated.

## Server Class

The Server class is idle until there is a packet in the queue at which point the packet moves into a buffer and service of the packet begins. The length of time it takes to service a packet is a function of the packet size in bits divided by the link speed in bits per second. Unlike the Generator, the Server takes the same amount of time to process a packet. The deterministic nature of the service time means that the Server has an upper limit to the number of packets per second that it can process. When the throughput limit of the Server is reached the packets will begin to accumulate on the packet queue. Once the service time expires, the packet is dispatched and the Server starts on the next packet in the queue. If there no packets are in the buffer or the queue then the Server is considered idle which is recoded by the Reporter for the metric.

## Reporter Class

The Reporter class is updated with the events that occurred each time slice and the data is stored internally in the Reporter. This process continues until the simulation time has expired and control of the application is returned to the Junit test. Both questions two and four required plots of the simulation results so a Reporter class was created that would record the results of a simulation and write the results to a specified Comma Separate Variable (CSV) file. Spreadsheet programs like Excel can import CSV natively, which made plotting the simulations significantly easier. Although the project did not specify either the JUnit tests or the Reporter class, the additional code made it much easier to compare simulation results.

## Performance Metrics

The performance metrics are handled by the Reporter class which is updated each turn with the events of a simulation time slice.

### Average queue size E[N]

For the average queue size E[N] metric the reporter stores a total sum of queue size per tick and then divides the sum by the total number of ticks for the simulation.

### Average sojourn time E[T]

For the average sojourn time E[T] the reporter stores a total sum of how long it takes a packet from arrival to departure each time a packet departs the server and then divides the sum by the total number of serviced packets for the simulation.

### Packet loss percentage

The packet loss percentage is calculated by recording the total number of packets lost by the total number of packets that arrived.

### Switch idle percentage

For the switch idle percentage metric the reporter stores a total sum of ticks that the queue was empty and then divides the sum by the total number of ticks for the simulation.

## Simulation Optimization

The simulation process is a balance between having accurate results and the length of time it takes to run a test. If a larger tick ratio is used then the total number of packets arrived would decline due to the random nature of the packet arrival rate. The larger the time slices between program cycles the more likely multiple packets could arrive in between a time slice. This would result in a skipped packet that never arrived in the queue and was never included in the final metrics. If a small tick ratio is used the simulation will take a long time to complete, however less skipped packets would occur. To pick an accurate tick ratio a series of simulations with the tick ratio ranging between one to one was conducted. We selected one as the point where the maximum arrival rate from question four had a steady state skipped packet rate. Using one tick ratio for both simulations gave us a good idea of where the metrics for the JUnit validation should be set to indicate a pass.

In an effort to both optimize the simulation run time and improve the simulation accuracy an event based simulator was developed. Instead of advancing time in incremental steps every loop, time would increment to the next event. Two events can occur in this simulation: when a packet arrives in the queue and after a packet is serviced. By advancing to the next event many idle program cycles are skipped which greatly improved the speed of the simulation. For comparison, the pre-optimized question four simulations, repeated 10 times with one tick ratio, took 27 minutes to complete. The post-optimization time for the same simulation took 16 seconds to complete, which is a speed improvement of 10125%. Most of speed in the post-optimization is gained from the fact that only two entities in this simulation can generate events. If more event generating entities where added to the simulation the gain in speed would be minimal. A more complicated simulation may benefit from advancing time in incremental steps if the number of event generating entities grows large.

When the idea of advancing time in events was purposed, there was some concern about the accuracy of the results. It was decided that the results of the optimized version should be compared to the original the verified the simulator. The concern was valid since some of the metrics, like the queue size, originally relied on the incremental summing of the queue size each tick and dividing it by the total number of ticks. To address these possible issues the reporter used the concept of a time delta to measure the length of time since the last update. For metrics like the average queue size each update the queue size is multiplied by the time delta and added to a queue size sum. The size of the queue will only change during an event so it is a safe assume that the queue size is the same for the duration of the time delta. The post-optimization results where similar to the original values and had a better standard deviation compared to the pre-optimized version. In theory, the accuracy is limited to the java double data type that stores the next packet arrival tick, which depends on the random variable U. If the random variable U is close to one the packet will arrive very closely to the previous packet and would be skipped if the tick time slice is too large. An event-based simulator would advance time as small as the possible resolution of the double type and should catch every packet that arrives. As a result the event based optimization improves both the speed and the accuracy of the simulator.

# Question 2

**Let L = 2000 bits and C = 1Mbps. Use your simulator to obtain the following graphs:**

Figure 2 E[N] as a function of ρ (for 0.2 < ρ < 0.9, step size 0.1).

Figure 3 E[T] as a function of ρ (for 0.2 < ρ < 0.9, step size 0.1).

Figure 4 P\_IDLE as a function of ρ (for 0.2 < ρ < 0.9, step size 0.1).

## Comment on Question 2 Results

As the network utilization increases linearly both the average queue size E[N] and average packet sojourn time E[T] increase exponentially while the percent idle timetime decreases exponentially. As approaches one the throughput speed limits the number of packets that can be processed a second. When more packets arrive than the switch can process the packets accumulate on the queue and E[N] will grow exponential by . The bigger the queue the longer the queue delay resulting in an exponential growth for E[T] as function of . If one or more packets are in the queue then the switch is no longer idle and will exponentially decrease as a function of . All of the plots for question two are dependent of how many packets are in the queue therefore the network utilization is a good indicator of the delay packets will experience end to end.

# Question 3

**Build a simulator for an M/D/1/K queue, and briefly explain your design.**

Both the M/D/1 and M/D/1/K simulators are very similar in functionality except that the M/D/1 has an infinite queue size whereas the M/D/1/K is limited to a queue size of K. To design the simulator so it works for both type of queues we defined the queue size value -1 to mean infinity. Thus, for question two all of the simulations were ran with the queue size as -1 and the value is ignored. For question four, the queue size was set to value of 10, 25, or 50 and then the value is included in the plot. For any queue size value other than -1 the queue size is checked before adding a new packet. If the packet would overflow the queue it is dropped and then recorded as a lost packet. The reporter records the lost packet so the packet loss percentage is calculated in the simulation’s report. Using this design, we are able to use the same source code for both types of queues.

# Question 4

**Let L=2000 bits and C=1 Mbps. Use your simulator to obtain the following graphs:**

Figure 5 E[N] as a function of ρ (for 0.5 < ρ < 1.5, step size 0.1), for K = 10, 25, 50 packets

Figure 6 E[T] as a function of ρ (for 0.5 < ρ < 1.5, step size 0.1), for K = 10, 25, 50 packets.

Figure 7 P\_LOSS as a function of ρ (for 0.5 < ρ < 1.5, step size 0.1) for K = 10, 25, 50 packets.

Figure 8 P\_IDLE as a function of ρ (for 0.5 < ρ < 1.5, step size 0.1) for K = 10, 25, 50 packets.

## Explanation of Obtaining P\_LOSS

To obtain the Reporter class records every instance of packet arriving at the queue and every instance a packet is lost. After the simulation is complete, the Reporter class calculates the packet loss percentage () by the following formulas:

## Comment on Question 4 Plots

The addition of a queue limit changed the dynamic of the model when the network utilization was greater than one. It was noticed that the total number of packets received from the Server class began to stabilize when was greater than one. After some investigation, it was discovered that the throughput limit of the switch had been reached and the switch began to drop packets. The link speed of the switch for both simulations was one Mbps and each packet was 2000 bits in length which meant a theoretical maximum throughput of 500 packets a second. The simulation results supports the theoretical maximum throughput as the simulation switch’s throughput averages to 500 packets a second for values of greater than one. As a result, all of the plots for question four have a significant data trend shift when the network utilization is approximately one.

For values of greater than one all of the metrics will reach an upper or lower limit based on the input parameters. The average queue size E[N] has a maximum value of K given a long simulation time and a high ratio. The maximum sojourn time of a packet enters a full queue is the service time multiplied by K + 1 seconds which is the limit of the average sojourn time E[T]. Both packet loss percentage and switch idle percentage have an upper limit of 100% and a lower limit of zero. It is unlikely will ever reach 100% since every time a packet is serviced space is made for an arriving packet in the queue meaning that some packets will be not be lost. So long as the packet arrival rate is greater than zero the will never be 100% since the switch will be non-idle for the length of service time of each arriving packet. So for extremely large values of the metrics will start to stabilize to their maximum limits.

# Source Code