MDRS Mini-Project 1

This is a report the First Mini-Project of MDRS university class, entitled **Performance Evaluation of Point-to-Point Links Supporting Packet Services**. The work carried out was conducted by:

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Exercise 1.a

Code

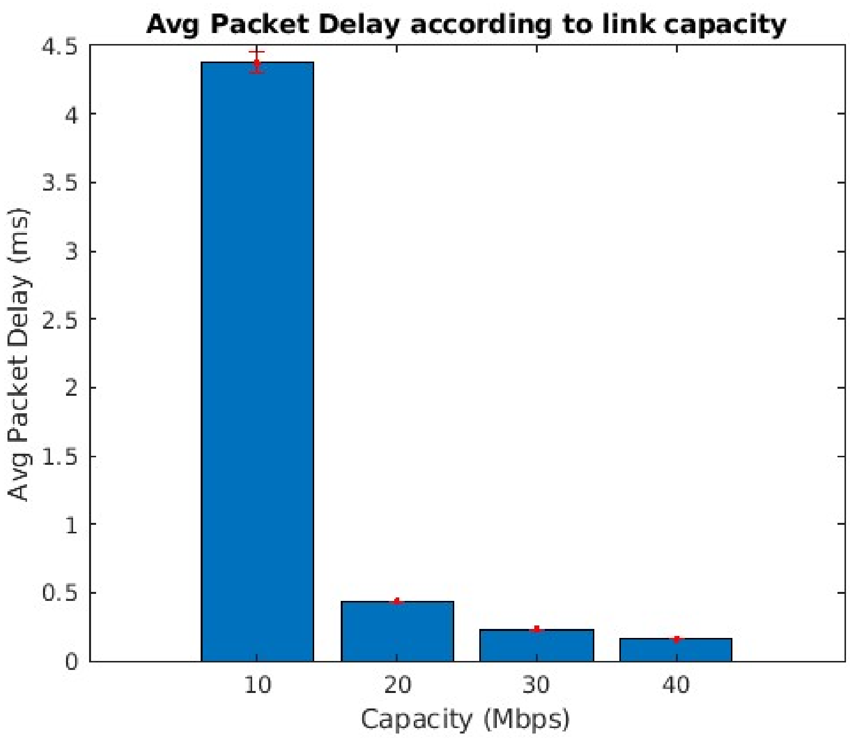
Taking advantage of the already developed *Simulator1* we used the *average_packet_delay* to process the data and return de average and confidence levels. Using a *for* we processed this information for all values of the Link capacity. A complete rundown of the code can be found bellow:

```
C = [10,20,30,40];
APD = zeros(length(C), 2);
for i=1:length(C)
    [APD(i,1), APD(i,2)] = average_packet_delay(C(i));
    fprintf('For C=%dMdps, the Av. Packet Delay (ms)  = %.2e +- %.2e\n',
C(i), APD(i,1), APD(i,2))
end

bar(C,APD(:,1));
hold on
xlabel = 'Capacity (Mbps)';
ylabel = 'Avg Packet Delay (ms)';
er = errorbar(C,APD(:,1),APD(:,2),APD(:,2), 'r.');
er.Color = [0 0 0];
er.LineStyle = 'none';
hold off

function [avg,trust]=average_packet_delay(capacity)
    N = 20;         %number of simulations
    Lambda = 1800;  %pps
    F = 1000000;    %Bytes
    P = 100000;
    PL = zeros(1,N); %vector with N simulation values
    APD = zeros(1,N); %vector with N simulation values
    MPD = zeros(1,N); %vector with N simulation values
```

```
    TT = zeros(1,N); %vector with N simulation values

    for it= 1:N
        [PL(it),APD(it),MPD(it),TT(it)] = Simulator1(Lambda, capacity, F,
P);
    end
    alfa= 0.1; % 90% confidence interval %
    avg = mean(APD);
    trust = norminv(1-alfa/2)*sqrt(var(APD)/N);
end
```

Result

The generated Bar plot is present in the image bellow. Take into account that the y-axis is the Average Packet delay (ms) and the x-axis, the Capacity (Mbps). The Confidence Interval with `C > 10` isn't clearly visible in the image due to the fact that the values are very small, so not easily visible.



The recorded values in the terminal were:

```
For C=10Mdps, the Av. Packet Delay (ms)  = 4.46e+00 +- 1.01e-01
For C=20Mdps, the Av. Packet Delay (ms)  = 4.35e-01 +- 1.31e-03
For C=30Mdps, the Av. Packet Delay (ms)  = 2.31e-01 +- 4.41e-04
For C=40Mdps, the Av. Packet Delay (ms)  = 1.57e-01 +- 2.52e-04
```

Conclusion

The results clearly indicate that increasing/doubling the Link Capacity will lead to lower average packet delays, since the link will support more bytes being sent per second (doubling the available bandwidth). It's extremely recommended for the link to have at least 20 Mbps of capacity, since the we can get more than 8 times lower packet delay compared to a 10 Mbps link. However, something should still be said about the law of diminishing returns, because after the 20 Mbps of link capacity the values are lower, but nowhere near the reduction noticed before. If a network operator wanted advice on the cables to buy and each upgraded link capacity costed double the price, clearly anything but essential services (and even then...) should use a 20 Mbps link. In summary, the effect of increasing link capacity and it's impact in average packet delay isn't linear. Smaller increases in capacity have more substantial impact when the link is initially congested, but the improvement slow down as higher link capacities are reached.

Exercise 1.b

Before calculating the Average Packet delay for all link capacities, we need to introduces some formulas and values:

- The Mean Service time is calculated by the heavy average of packet size divided by the link capacity (C), with $S = packet\_size$ **in bytes** and $P = packet\_probability$ expressed $[0, 1]$:

$$E[S] = \sum_{i=1}^{\infty} \frac{S_i}{C} \times P_i$$

- Second moment of the Service time (or Variance of the service time):

$$E[S^2] = \sum_{i=1}^{\infty} \frac{S_i^2}{C} \times P_i$$

- The *Pollaczek-Khinchine* formula is used to calculate the average waiting time (WQ) **in an M/G/1 queue**:

$$W_Q = \frac{\lambda E[S]}{2(1 - \lambda E[S])}$$

- With the *Pollaczek-Khinchine* formula we can calculate the average packet delay as:

$$W = W_q + E[S]$$

- $\lambda = 1800$pps (Packets Per Second)

With this formulas in mind and with the help of Matlab, we'll proceed in calculating the Average Packet delay for each Capacity:

- For $C = 10$:

$$W_Q = \frac{\lambda E[S]}{2(1 - \lambda E[S])} = \frac{1800 \times 4.96 \times 10^{-4}}{2(1 - 1800 \times 4.96 \times 10^{-4})} = 3.8923 \text{ ms}$$

$$W = W_Q + E[S] = 3.8923 + 4.96 \times 10^{-4}$$

$$\equiv W = 4.3883 \text{ ms}$$

- For $C = 20$:

$$W_Q = \frac{1800 \times 2.48 \times 10^{-4}}{2(1 - 1800 \times 2.48 \times 10^{-4})} = 0.1884 \text{ ms}$$

$$W = W_Q + E[S] = 0.1884 + 2.48 \times 10^{-4}$$

$$\equiv W = 0.4364 \text{ ms} = 4.364 \times 10^{-1} \text{ ms}$$

- For $C = 30$:

$$W_Q = \frac{1800 \times 2.48 \times 10^{-4}}{2(1 - 1800 \times 2.48 \times 10^{-4})} = 0.0660 \text{ ms}$$

$$W = W_Q + E[S] = 0.1884 + 1.65 \times 10^{-4}$$

$$\equiv W = 0.2313 \text{ ms} = 2.313 \times 10^{-1} \text{ ms}$$

- For $C = 40$:

$$W_Q = \frac{1800 \times 1.24 \times 10^{-4}}{2(1 - 1800 \times 1.24 \times 10^{-4})} = 0.0336 \text{ ms}$$

$$W = W_Q + E[S] = 0.0336 + 1.24 \times 10^{-4}$$

$$\equiv W = 0.1576 \text{ ms} = 1.576 \times 10^{-1} \text{ ms}$$

Conclusion:

Analyzing the resulting data indicates that as link capacity is increased, the Average Packet Transmission time is decreased, resulting in lower queueing delays (W_q) and Average Packet Delay (W). The theoretical results obtained are very similar with what was achieved on the Simulation performed in exercise 1.a. Although the Simulation uses a more real-world approach on obtaining the data, it comes at a cost of performance. The Theoretical approach using the **M/G/1 model** is processed almost instantly and since the obtained values are very close, we can use them when decision making, instead of always needing to simulate the use-cases.

Matlab Script code and output

```
C = [10,20,30,40]; % Mbps
```

```
for i=1:length(C)
    capacity = C(i)*10^6;
    fprintf('For C=%d:\n', C(i));
    prob_left = (1 - (0.19 + 0.23 + 0.17)) / ((109 - 65 + 1) + (1517 - 111 + 
1));
    avg_bytes = 0.19*64 + 0.23*110 + 0.17*1518 + sum((65:109)*(prob_left)) + 
sum((111:1517)*(prob_left));
    avg_time = avg_bytes * 8 / capacity;

    fprintf("\tAverage packet size is: %.2f Bytes\n", avg_bytes);
    fprintf("\tAverage packet trasmission time is: %.2e seconds\n", 
avg_time);
    x = 64:1518;
    s = (x .* 8) ./ (capacity);
    s2 = (x .* 8) ./ (capacity);
    for i = 1:length(x)
        if i == 1
            s(i) = s(i) * 0.19;
            s2(i) = s2(i)^2 * 0.19;
        elseif i == 110-64+1
            s(i) = s(i) * 0.23;
            s2(i) = s2(i)^2 * 0.23;
        elseif i == 1518-64+1
            s(i) = s(i) * 0.17;
            s2(i) = s2(i)^2 * 0.17;
        else
            s(i) = s(i) * prob_left;
            s2(i) = s2(i)^2 * prob_left;
        end
    end

    Es = sum(s);
    Es2 = sum(s2);

    fprintf('\tE[S] = %.2e seconds\n', Es);
    fprintf('\tE[S2] = %.2e seconds\n', Es2);

    Wq = (K * Es2) / (2 * (1 - K * Es));
    W = Wq + Es;% W = Wq + E[s]
    fprintf('\tWq = %.4f ms\n', Wq*1000);
    fprintf('\tW = %.4f ms\n', W*1000);

end
```

The script originated the following terminal output:

```
For C=10:
        Average packet size is: 620.02 Bytes
        Average packet trasmission time is: 4.96e-04 seconds
        E[S] = 4.96e-04 seconds
        E[S2] = 4.63e-07 seconds
        Wq = 3.8923 ms
        W = 4.3883 ms
For C=20:
```

```
        Average packet size is: 620.02 Bytes
        Average packet trasmission time is: 2.48e-04 seconds
        E[S] = 2.48e-04 seconds
        E[S2] = 1.16e-07 seconds
        Wq = 0.1884 ms
        W = 0.4364 ms
For C=30:
        Average packet size is: 620.02 Bytes
        Average packet trasmission time is: 1.65e-04 seconds
        E[S] = 1.65e-04 seconds
        E[S2] = 5.15e-08 seconds
        Wq = 0.0660 ms
        W = 0.2313 ms
For C=40:
        Average packet size is: 620.02 Bytes
        Average packet trasmission time is: 1.24e-04 seconds
        E[S] = 1.24e-04 seconds
        E[S2] = 2.90e-08 seconds
        Wq = 0.0336 ms
        W = 0.1576 ms
```

Exercise 1.c

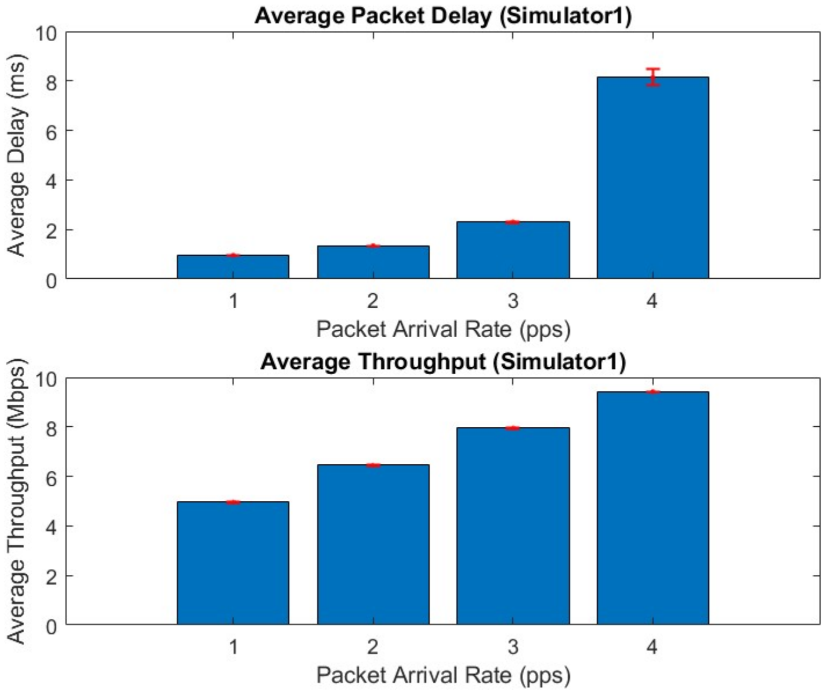
Code

In Exercise 1.c, we utilized the "Simulator1" to evaluate network performance under specific link bandwidth and queue size configurations. We conducted 20 simulations for varying packet arrival rates (λ) and computed average packet delay and throughput, accompanied by 90% confidence intervals. The provided MATLAB code offers insights into our approach, covering simulation execution, data analysis, and results visualization using bar charts with error bars. This method allowed for a comprehensive exploration of how different packet arrival rates influence network performance.

```
C = 10;                 % Link bandwidth (Mbps)
f = 1e6;                % Queue size (Bytes)
P = 1e5;                % Stopping criterion (number of packets)
lambda_values = [1000, 1300, 1600, 1900];  % Packet arrival rate (pps)

% Vectors to store the results
average_packet_delay = zeros(length(lambda_values), 1);
average_throughput = zeros(length(lambda_values), 1);
confidence_intervals_delay = zeros(length(lambda_values), 2);
confidence_intervals_throughput = zeros(length(lambda_values), 2);

% Run the simulator 20 times for each lambda value
for i = 1:length(lambda_values)
    lambda = lambda_values(i);
    num_simulations = 20;
    delays = zeros(num_simulations, 1);
    throughputs = zeros(num_simulations, 1);

    for j = 1:num_simulations
        [PL, APD, ~, TT] = Simulator1(lambda, C, f, P);
        delays(j) = APD;
        throughputs(j) = TT;
    end

    % Calculate the mean and 90% confidence interval
    average_packet_delay(i) = mean(delays);
    confidence_intervals_delay(i, :) = prctile(delays, [5, 95]);

    average_throughput(i) = mean(throughputs);
    confidence_intervals_throughput(i, :) = prctile(throughputs, [5, 95]);
end

% Bar Charts
figure;
```

```
subplot(2, 1, 1);
bar(average_packet_delay);
title('Average Packet Delay (Simulator1)');
xlabel('Packet Arrival Rate (pps)');
ylabel('Average Delay (ms)');
hold on;
errorbar(1:length(lambda_values), average_packet_delay, average_packet_delay
- confidence_intervals_delay(:, 1), confidence_intervals_delay(:, 2) -
average_packet_delay, 'r.', 'LineWidth', 1);

subplot(2, 1, 2);
bar(average_throughput);
title('Average Throughput (Simulator1)');
xlabel('Packet Arrival Rate (pps)');
ylabel('Average Throughput (Mbps)');
hold on;
errorbar(1:length(lambda_values), average_throughput, average_throughput -
confidence_intervals_throughput(:, 1), confidence_intervals_throughput(:, 2)
- average_throughput, 'r.', 'LineWidth', 1);
```

Result



Conclusion

Exercise 1.d

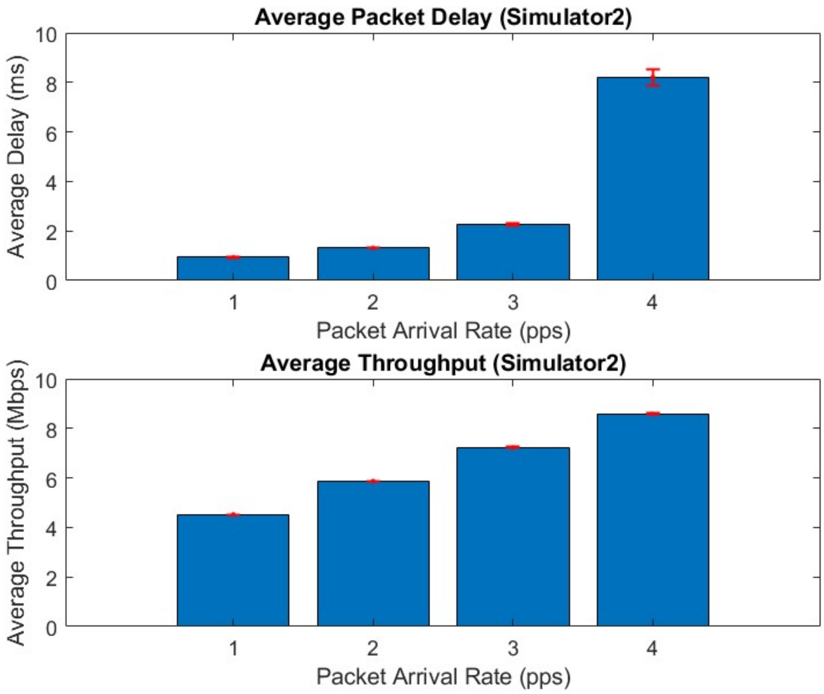
Code

In Exercise 1.d, we revisit the network performance assessment carried out in Exercise 1.c. However, this time, we utilize "Simulator2" with a bit error rate (BER) parameter, b = 10^-5. We aim to evaluate the influence of BER on network behavior. Similar to Exercise 1.c, we execute 20 simulations for each of the specified packet arrival rates (λ). Key performance metrics, including average packet delay and throughput, are computed, and their associated 90% confidence intervals are derived. The subsequent MATLAB code illustrates our approach to conducting these simulations, processing the data, and presenting the results in bar charts with error bars. This approach enables a comprehensive comparison of network performance between Exercise 1.c and 1.d and draws conclusions regarding the impact of BER on the obtained results.

```
C = 10;                % Link bandwidth (Mbps)
f = 1e6;               % Queue size (Bytes)
P = 1e5;               % Stopping criterion (number of packets)
b = 1e-5;              % Bit error rate
lambda_values = [1000, 1300, 1600, 1900];  % Packet arrival rate (pps)

% Vectors to store the results for Simulator2
average_packet_delay_sim2 = zeros(length(lambda_values), 1);
average_throughput_sim2 = zeros(length(lambda_values), 1);

% Run the simulations for each lambda value and the specified BER
for i = 1:length(lambda_values)
    lambda = lambda_values(i);
    num_simulations = 20;
    delays_sim2 = zeros(num_simulations, 1);
    throughputs_sim2 = zeros(num_simulations, 1);

    for j = 1:num_simulations
        [PL, APD, ~, TT] = Simulator2(lambda, C, f, P, b);
        delays_sim2(j) = APD;
        throughputs_sim2(j) = TT;
    end

    % Calculate the mean for Simulator2
    average_packet_delay_sim2(i) = mean(delays_sim2);
    average_throughput_sim2(i) = mean(throughputs_sim2);
end

% Display the results in bar charts for Simulator2
```

```
figure;
subplot(2, 1, 1);
bar(average_packet_delay_sim2);
title('Average Packet Delay (Simulator2)');
xlabel('Packet Arrival Rate (pps)');
ylabel('Average Delay (ms)');
hold on;
errorbar(1:length(lambda_values), average_packet_delay_sim2,
average_packet_delay_sim2 - confidence_intervals_delay(:, 1),
confidence_intervals_delay(:, 2) - average_packet_delay_sim2, 'r.',
'LineWidth', 1);

subplot(2, 1, 2);
bar(average_throughput_sim2);
title('Average Throughput (Simulator2)');
xlabel('Packet Arrival Rate (pps)');
ylabel('Average Throughput (Mbps)');
hold on;
errorbar(1:length(lambda_values), average_throughput_sim2,
average_throughput_sim2 - confidence_intervals_throughput(:, 1),
confidence_intervals_throughput(:, 2) - average_throughput_sim2, 'r.',
'LineWidth', 1);
```

Result



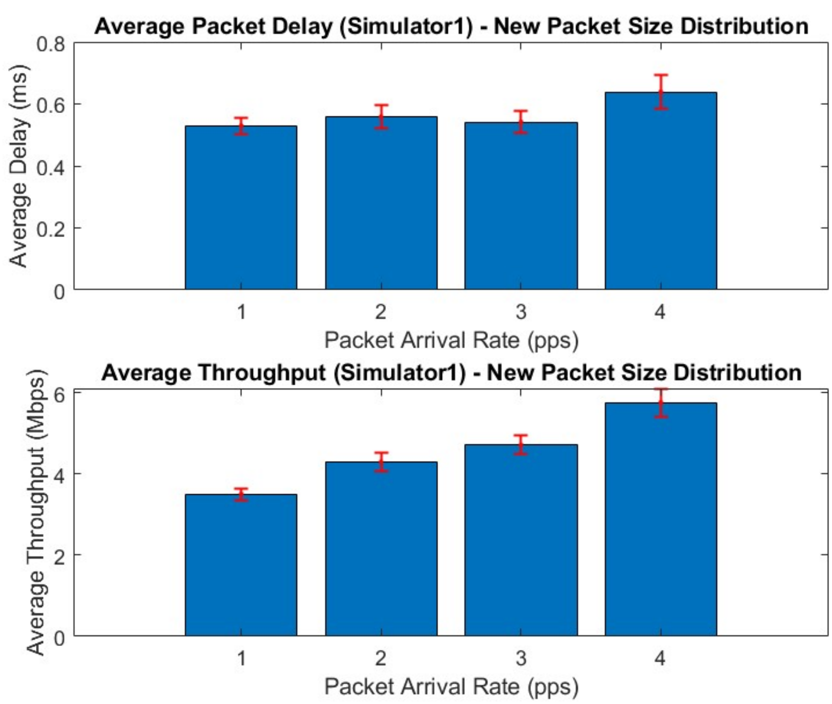
Exercise 1.e

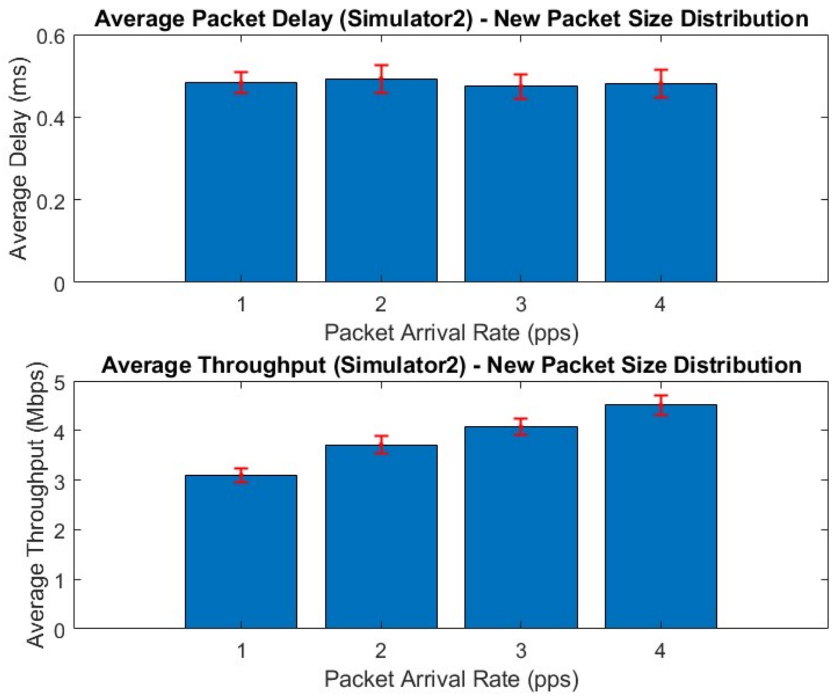
Code

Considering the same packet size as present in the Simulators, just the new probabilities, we just needed to modify the *GeneratePacketSize* function in both the simulators.

```
function out= GeneratePacketSize()
    aux= rand();
    aux2= [65:109 111:1517];
    if aux <= 0.25
        out= 64;
    elseif aux <= 0.25 + 0.17
        out= 110;
    elseif aux <= 0.25 + 0.17 + 0.11
        out= 1518;
    else
        out = aux2(randi(length(aux2)));
    end
end
```

Result





Average Packet Delay (Simulator2) - New Packet Size Distribution
Average Delay (ms)
0.6
0.4
0.2
0
1
2
3
4
Packet Arrival Rate (pps)
Average Throughput (Simulator2) - New Packet Size Distribution
Average Throughput (Mbps)
5
4
3
2
1
0
1
2
3
4
Packet Arrival Rate (pps)

Conclusion

Exercise 2.a

Modifications or insertions in the code

In order to obtain the Average Packet Queuing Delay, some changes needed to be made to Simulator3, mainly the introduction of four new variables:

- `TotalQueuingDelayData` - Holds the Queuing times of all **data** packets
- `TotalQueuingDelayVoip` - Holds the Queuing times of all **voip** packets
- `AQDdata` - Calculates the Average Queuing Delay of **data** packets, by the ratio of Queuing times with the total transmitted **data** packets.
- `AQDvoip` - Calculates the Average Queuing Delay of **voip** packets, by the ratio of Queuing times with the total transmitted **voip** packets. This changes involved incrementing the variables of Queuing times, when the packet are **Departing**, and a check to not count the last packet, as it may not be received, so shouldn't be counted (with higher thresholds won't make a difference, but in lower it'll affect the results). This changes can be observed in the following code:

```
function [PLdata, PLvoip , APDdata, APDvoip , AQDdata, AQDvoip, MPDdata,
MPDvoip , TT] = Simulator3(lambda,C,f,P,n)
(...)
MAXDELAYvoip= 0;            % Maximum delay among all transmitted voip
packets
TotalQueuingDelayData= 0;
TotalQueuingDelayVoip= 0;

% Initializing the simulation clock:
Clock= 0;
(...)

while (TRANSMITTEDPACKETSdata+TRANSMITTEDPACKETSvoip)<P               %
Stopping criterium
    (...)                  % Eliminate first event
    if Event == ARRIVAL            % If first event is an ARRIVAL
        (...)
    else                           % If first event is a DEPARTURE
        (...)

        if QUEUEOCCUPATION > 0
            Event_List = [Event_List; DEPARTURE, Clock +
8*QUEUE(1,1)/(C*10^6), QUEUE(1,1), QUEUE(1,2), QUEUE(1,3)];
            QUEUEOCCUPATION= QUEUEOCCUPATION - QUEUE(1,1);
            if (TRANSMITTEDPACKETSdata+TRANSMITTEDPACKETSvoip)<P
                if QUEUE(1,3) == VOIP
```

```
                    TotalQueuingDelayVoip = TotalQueuingDelayVoip + (Clock - 
QUEUE(1,2));
                else
                    TotalQueuingDelayData = TotalQueuingDelayData + (Clock - 
QUEUE(1,2));
                end
            end

            QUEUE(1,:)= [];
        else
            STATE= 0;
        end
    end
end

(...)
APDvoip= 1000*DELAYSvoip/TRANSMITTEDPACKETSvoip;   % in milliseconds
AQDdata= 1000*TotalQueuingDelayData/TRANSMITTEDPACKETSdata;   % in 
milliseconds
AQDvoip= 1000*TotalQueuingDelayVoip/TRANSMITTEDPACKETSvoip;   % in 
milliseconds
MPDdata= 1000*MAXDELAYdata;                    % in milliseconds
(...)
```

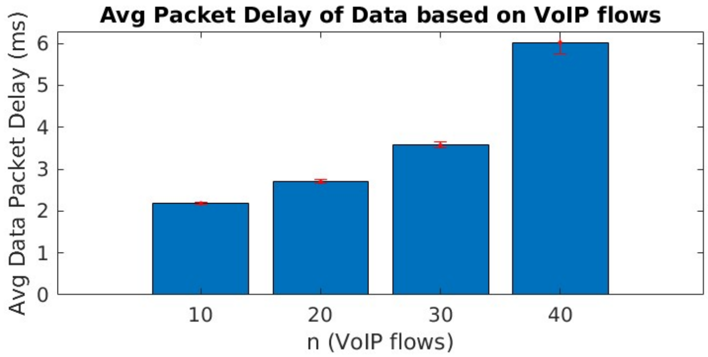
In the script to launch the Simulator, we just want to point out the function that accepts the modifiable n VoIP flow numbers and calculates all the necessary attributes:

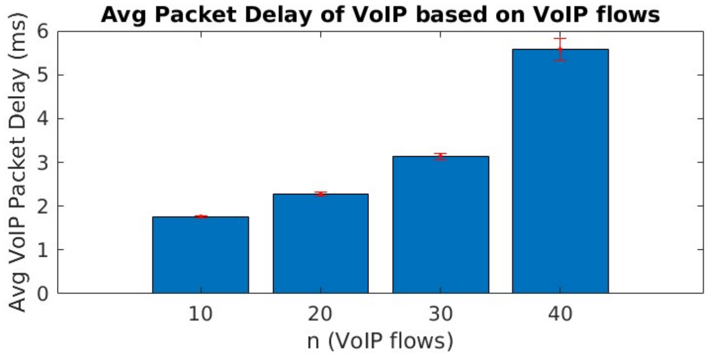
```
function [(avg_data,trust_data, avg_voip, trust_voip, avg_queue_data, 
trust_queue_data, avg_queue_voip, trust_queue_voip)]=average_packet_delay(n)
    Iter = 20;          %number of simulations
    Lambda = 1500;   %pps
    F = 1000000;     %Bytes
    P = 100000;
    C = 10;
    APDdata = zeros(1,Iter); %vector with N simulation values
    APDvoip = zeros(1,Iter); %vector with N simulation values
    AQDdata = zeros(1,Iter); %vector with N simulation values
    AQDvoip = zeros(1,Iter); %vector with N simulation values

    for it= 1:Iter
        [~,~,APDdata(it),APDvoip(it),AQDdata(it),AQDvoip(it),~,~,~] = 
Simulator3(Lambda, C, F, P, n);
    end
    alfa= 0.1; % 90% confidence interval %
    avg_data = mean(APDdata);
    trust_data = norminv(1-alfa/2)*sqrt(var(APDdata)/Iter);
    avg_voip = mean(APDvoip);
    trust_voip = norminv(1-alfa/2)*sqrt(var(APDvoip)/Iter);
    avg_queue_data = mean(AQDdata);
    trust_queue_data = norminv(1-alfa/2)*sqrt(var(AQDdata)/Iter);
    avg_queue_voip = mean(AQDvoip);
    trust_queue_voip = norminv(1-alfa/2)*sqrt(var(AQDvoip)/Iter);
end
```

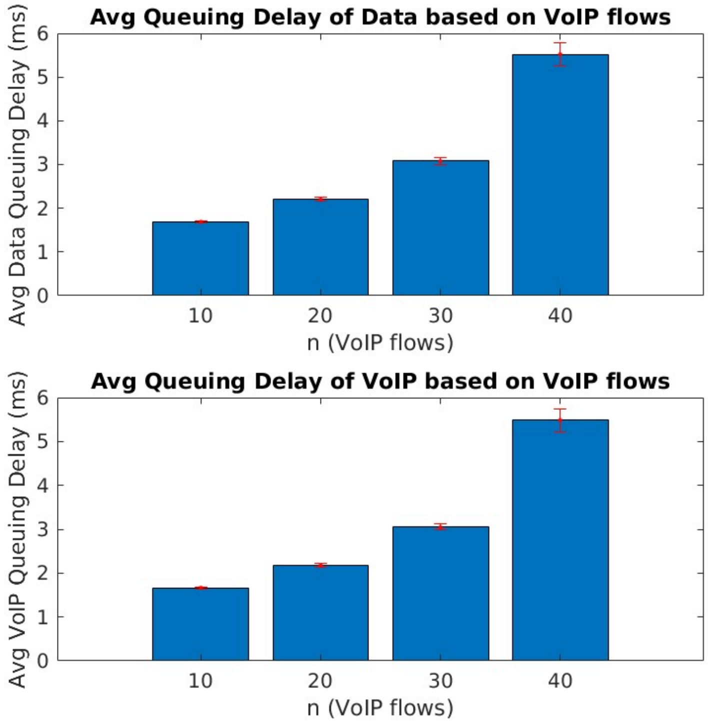
Result

Executing the matlab script resulted the following terminal output and images.

```
For n=10:
        VoIP flows, the APD of data (ms)  = 2.18e+00 +- 2.60e-02
        VoIP flows, the APD of VoIP (ms)  = 1.76e+00 +- 2.33e-02
        VoIP flows, the AQD of data (ms)  = 1.69e+00 +- 2.57e-02
        VoIP flows, the AQD of VoIP (ms)  = 1.67e+00 +- 2.33e-02
For n=20:
        VoIP flows, the APD of data (ms)  = 2.70e+00 +- 4.46e-02
        VoIP flows, the APD of VoIP (ms)  = 2.27e+00 +- 4.15e-02
        VoIP flows, the AQD of data (ms)  = 2.20e+00 +- 4.42e-02
        VoIP flows, the AQD of VoIP (ms)  = 2.18e+00 +- 4.15e-02
For n=30:
        VoIP flows, the APD of data (ms)  = 3.58e+00 +- 7.10e-02
        VoIP flows, the APD of VoIP (ms)  = 3.14e+00 +- 6.82e-02
        VoIP flows, the AQD of data (ms)  = 3.08e+00 +- 7.07e-02
        VoIP flows, the AQD of VoIP (ms)  = 3.05e+00 +- 6.82e-02
For n=40:
        VoIP flows, the APD of data (ms)  = 6.02e+00 +- 2.64e-01
        VoIP flows, the APD of VoIP (ms)  = 5.58e+00 +- 2.59e-01
        VoIP flows, the AQD of data (ms)  = 5.52e+00 +- 2.64e-01
        VoIP flows, the AQD of VoIP (ms)  = 5.49e+00 +- 2.59e-01
```







As we can see by the terminal output and the images, Both **Average Packet Delay** and **Average Queuing Delay** show an increase in time, as the number of VoIP flows increases. This is due to the higher traffic generated by the increasing VoIP flows, competing for more resources of a limited bandwidth/link capacity. Since Simulator 3 doesn't implement priorities with the Data and VoIP packets, both types of packets have the same treatment in the FIFO queue. Which means that as observed in the images, the delays are similar for both of them. This results indicate the need to establish priorities in the FIFO queue, since generally the VoIP should have lower delays than other packet types, given the higher time-sensitivity of the data. This same situation will be approached in the following exercise.