**Departamento de Eletrónica, Telecomunicações e Informática**

**Mestrado Integrado em Eng. de Computadores e Telemática**

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# Desempenho e Dimensionamento de Redes

## Assignment Guide No. 3

## Performance of a Packet Switching Connection

## Assignment Description

Implement the following tasks using MATLAB to obtain the requested numerical solutions and conclusions. At the end, submit a report with the answers to the questions of the tasks requested for reporting including the numerical results, the MATLAB codes duly explained and the requested conclusions.

### Task 1

Consider the event driven simulator, implemented in the provided MATLAB function *Simulator1*, to estimate the performance of a point-to-point IP connection between a company router and its ISP (Internet Service Provider). The simulator only considers the downstream direction, *i.e.*, from ISP to the company (usually, the direction with highest traffic load).

*Simulator1* considers a connection of $C$ (in Mbps) and a queue of size $f$ (in Bytes) with a FIFO (First-In-First-Out) queueing discipline. The packet flow submitted to the connection is characterized by: (i) an exponentially distributed time between packet arrivals with average $1/\lambda_{data}$ and (ii) a random packet size between 64 and 1518 bytes with the probabilities: 16% for 64 bytes, 25% for 110 bytes, 20% for 1518 bytes and an equal probability for all other values (i.e., from 65 to 109 and from 111 to 1517).

Input parameters of *Simulator1*:

- $\lambda_{data}$ – packet rate, in packets per second (pps)
- $C$ – connection capacity, in Mbps
- $f$ – queue size, in Bytes
- $P$ – total number of transmitted packets of a simulation run

Performance parameters estimated by *Simulator1*:

- PL – Packet Loss (%)
- APD – Average Packet Delay (milliseconds)
- MPD – Maximum Packet Delay (milliseconds)
- TT – Transmitted Throughput (Mbps)

Stopping criteria of *Simulator1*:

- Time instant when the connection ends the transmission of the $P^{th}$ packet ($P$ is one the of input parameter); in *Simulator1*, the queued packets at the end of the simulation do not count for the performance estimation.

*Simulator1* is based on the following variables:

Events: ARRIVAL (the arrival of a packet) and DEPARTURE (the transmission end of a packet).

State variables: STATE (binary variable indicating if the connection is free or busy with the transmission of a packet), QUEUEOCCUPATION (occupation of the queue, in number of bytes, with the queued packets) and QUEUE (matrix with a variable number of rows and with 2 columns where each column has the size and the arriving time instant of each packet in the queue).

Statistical counters: TOTALPACKETS (number of packets arrived to the system), LOSTPACKETS (number of packets dropped due to buffer overflow), TRANSMITTEDPACKETS (number of transmitted packets), TRANSMITTEDBYTES (sum of the bytes of the transmitted packets), DELAYS (sum of the delays of the transmitted packets), MAXDELAY (maximum delay among all transmitted packets).

Based on the statistical counters, the performance parameters are estimated at the end as:

PL = 100 × LOSTPACKETS / TOTALPACKETS
APD = 1000 × DELAYS / TRANSMITTEDPACKETS
MPD = 1000 × MAXDELAY
TT = $10^{-6}$ × TRANSMITTEDBYTES × 8 / total simulated time

**1.a.** Develop a MATLAB script to run *Simulator1* 10 times with a stopping criterion of $P$ = 10000 at each run and to compute the estimated values and the 90% confidence intervals of all performance parameters when $\lambda$ = 1800 pps, $C$ = 10 Mbps and $f$ = 1.000.000 Bytes (~1 MByte). Results (recall that these are simulation results):

```
Packet Loss (%)        = 0.00e+00 +- 0.00e+00
Av. Packet Delay (ms)  = 7.46e+00 +- 9.55e-01
Max. Packet Delay (ms) = 3.43e+01 +- 4.80e+00
Throughput (Mbps)      = 9.33e+00 +- 5.25e-02
```

**1.b.** Repeat the previous experiment but now consider $f$ = 10.000 Bytes (~10 KBytes) Justify the differences between these results and the previous results. Results (recall that these are simulation results):

```
Packet Loss (%)        = 1.69e+00 +- 1.52e-01
Av. Packet Delay (ms)  = 3.42e+00 +- 8.40e-02
Max. Packet Delay (ms) = 9.02e+00 +- 3.53e-02
Throughput (Mbps)      = 9.02e+00 +- 5.51e-02
```

**1.c.** Consider that the system is modelled by a $M/M/1$ queueing model[1]. Determine the theoretical values of the packet loss, average packet delay and total throughput using the $M/M/1$ model for the parameters considered in **1.a**. Compare these values with the simulation values and take conclusions. Results:

```
Packet Loss (%)        = 0.0000
Av. Packet Delay (ms)  = 8.1275
Throughput (Mbps)      = 9.3602
```

**1.d.** Consider that the system is modelled by a $M/G/1$ queueing model[2]. Determine the theoretical values of the packet loss, average packet delay and total throughput using the $M/G/1$ model for the parameters considered in **1.a**. Compare these values with the theoretical values of $M/M/1$ and with the simulation values, and take conclusions. Results:

```
Packet Loss (%)        = 0.0000
Av. Packet Delay (ms)  = 7.5185
Throughput (Mbps)      = 9.3602
```

[1] Check the $M/M/1$ queueing model in slides 29-30 of the theoretical presentation of Module 2 and slide 16 in the theoretical presentation of Module 4.

[2] Check the $M/G/1$ queueing model in slides 38-39 of Module 2 and the resolution of Exemple 4 of Module 2.

**1.e.** Consider that the system is modelled by a $M/M/1/m$ queueing model[3]. Determine the theoretical values of the packet loss, average packet delay and throughput using the $M/M/1/m$ model for the parameters considered in **1.b**. Compare these values with the simulation values and take conclusions. Results:

```
Packet Loss (%)        = 3.2906
Av. Packet Delay (ms)  = 3.7028
Throughput (Mbps)      = 9.0522
```

## Task 2

In the previous task, it was assumed that the connection between the company router and its ISP (Internet Service Provider) does not introduce any transmission/propagation errors (i.e., it is provided by a wired access network). In this task, we assume that the connection is provided by a wireless access (for example, through a 4G/5G mobile network).

Develop *Simulator2* by changing the previous *Simulator1* in order to consider that the connection introduces a BER (Bit Error Rate) given by $b$. The input parameters of *Simulator2* should be all the input parameters of *Simulator1* plus parameter $b$. The performance parameters estimated by *Simulator2* should be the same as the ones of the previous simulator.

**2.a.** Run *Simulator2* 20 times with a stopping criterion of $P$ = 10000 at each run to compute the estimated values and the 90% confidence intervals of all performance parameters when $\lambda$ = 1800 pps, $C$ = 10 Mbps, $f$ = 1.000.000 Bytes (~1 MByte) and the BER is $b = 10^{-6}$. Results (recall that these are simulation results):

```
Packet Loss (%)        = 4.94e-01 +- 2.42e-02
Av. Packet Delay (ms)  = 7.37e+00 +- 6.20e-01
Max. Packet Delay (ms) = 3.56e+01 +- 3.53e+00
Throughput (Mbps)      = 9.24e+00 +- 3.65e-02
```

**2.b.** Repeat the previous experiment but now consider that the BER is $b = 10^{-5}$. Justify the differences between these results and the previous results. Results (recall that these are simulation results):

```
Packet Loss (%)        = 5.07e+00 +- 1.11e-01
Av. Packet Delay (ms)  = 7.03e+00 +- 5.07e-01
Max. Packet Delay (ms) = 3.21e+01 +- 2.72e+00
Throughput (Mbps)      = 8.49e+00 +- 3.70e-02
```

**2.c.** Consider that the system is modelled by a $M/G/1$ queueing model. Determine the theoretical values of the packet loss, average packet delay and total throughput using the $M/G/1$ model for the parameters considered in **2.a** (see **Appendix A**). Compare these values with the values in **1.d** and the simulation values in **2.a**, and take conclusions. Results:

```
Packet Loss (%)        = 0.5175
Av. Packet Delay (ms)  = 7.5163
Throughput (Mbps)      = 9.2711
```

[3] Check the $M/M/1/m$ queueing model in slides 34-35 of the theoretical presentation of Module 2 and slide 17 of the theoretical presentation of Module 4.

**2.d.** Considering again the system modelled by a *M*/*G*/1 queueing model, determine now the theoretical values of the packet loss, average packet delay and total throughput for the parameters considered in **2.b**. Compare these values with the values in **1.d** and **2.c**, and with the simulation values in **2.c**, and take conclusions. Results:

```
Packet Loss (%)         = 4.9601
Av. Packet Delay (ms)   = 7.4961
Throughput (Mbps)       = 8.5115
```

## Task 3 – for reporting (evaluation weight = 50%)

**3.a.** Consider the connection characterized by $C$ = 10 Mbps, $f = 10^7$ Bytes (~10 MBytes) and BER $b$ = 0. Run *Simulator2* 10 times with a stopping criterion of $P$ = 10000 at each run to compute the estimated values and the 90% confidence intervals of all performance parameters when $\lambda$ = 1500, 1600, 1700, 1800, 1900 and 2000 pps. Present the results and the confidence intervals in bar charts with error bars[4].

**3.b.** Repeat the previous experiment **3.a** now running the simulator 40 times for each case. Again, present the results and the confidence intervals in bar charts with error bars. Justify the obtained results for the different performance parameters. Take also conclusions of the impact of the number of simulation runs on the obtained confidence intervals of the different cases.

**3.c.** For each of the previous cases, compute the average packet delay and the total throughput of the connection considering that it is modelled by a *M*/*M*/1 system and by a *M*/*G*/1 system. Present both theoretical values and the simulation results of **3.b** (without confidence intervals) in a bar chart for the average packet delay and another bar chart for the total throughput. Take conclusions on how close each theoretical model is from the simulation results of the different cases.

**3.d.** Consider the packet rate $\lambda$ = 1800 pps and the connection characterized by $C$ = 10 Mbps and BER $b$ = 0. Run *Simulator2* 40 times with a stopping criterion of $P$ = 10000 at each run to compute the estimated values and the 90% confidence intervals of all performance parameters when $f$ = 2500, 5000, 7500, 10000, 12500, 15000, 17500 and 20000 Bytes. Present the results and the confidence intervals in bar charts with error bars. Justify the obtained results.

**3.e.** For each of the previous cases of experiment **3.d**, compute the packet loss, the average packet delay and the total throughput of the connection considering that it is modelled by a *M*/*M*/1/*m*. Present both theoretical values and the simulation results of **3.d** (without confidence intervals) in a bar chart for the packet loss, another bar chart for the average packet delay and a third bar chart for the total throughput. Take conclusions on how close the theoretical model is from the simulation results of the different cases.

**3.f.** Repeat the previous experiment **3.d** considering now that the connection has a BER of $b = 10^{-5}$. Present the results and the confidence intervals in bar charts with error bars. Justify the obtained results comparing them with the simulation results of experiment **3.d**.

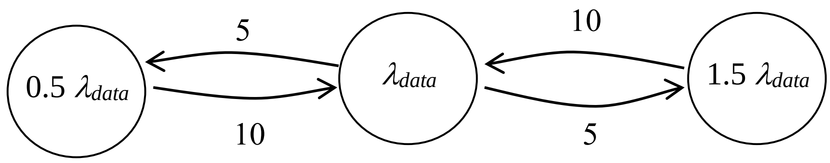
[4] https://www.mathworks.com/help/matlab/creating_plots/bar-chart-with-error-bars.html

**3.g.** Repeat experiment **3.b** considering now that the connection has a BER of $b = 10^{-5}$. Present the results and the confidence intervals in bar charts with error bars. Justify the obtained results comparing them with the simulation results of experiment **3.b**.

**3.h.** For each of the previous cases of experiment **3.g**, compute the average packet delay and the total throughput of the connection considering that it is modelled by a *M*/*G*/1 system. Present both theoretical values and the simulation results of **3.g** (without confidence intervals) in a bar chart for the average packet delay and another bar chart for the total throughput. Take conclusions on how close the theoretical model is from the simulation results of the different cases.

## Task 4 – for reporting (evaluation weight = 50%)

In the previous tasks, it was assumed that the packet flow submitted to the connection is a Poisson process with a rate $\lambda_{data}$ (i.e., it is characterized by an exponentially distributed time between packet arrivals with average $1/\lambda_{data}$). In this task, consider that the packet flow submitted to the connection is modeled by the following Markov chain:




where transition rates are in $sec^{-1}$ and at each state the flow submitted to the connection is a Poisson process with rate $0.5\ \lambda_{data}$, $\lambda_{data}$, and $1.5\ \lambda_{data}$, respectively. Develop *Simulator3* by changing the previous *Simulator2* in order to simulate this case. Both input parameters and (output) performance parameters of *Simulator3* should be the same as the ones of the previous *Simulator2*. To develop *Simulator3*, consider the following additional variables:

Event: TRANSITION (the transition of a state in the packet arriving Markov chain).

State variable: FLOWSTATE (integer variable that can be 1, 2 or 3 indicating which is the current state of the packet arriving Markov chain that must be initialized according to the probability of each state).

**4.a.** Run *Simulator3* 10 times with a stopping criterion of $P$ = 100000 at each run to estimate all performance parameters and their 90% confidence intervals when $\lambda$ = 1800 pps, $C$ = 10 Mbps, $f = 10^6$ Bytes (~1 MByte) and the BER is $b$ = 0. Results (recall that these are simulation results):

```
PacketLoss (%)          = 4.24e-02 +- 6.98e-02
Av. Packet Delay (ms)   = 1.32e+02 +- 2.03e+01
Max. Packet Delay (ms)  = 5.73e+02 +- 7.41e+01
Throughput (Mbps)       = 9.32e+00 +- 7.42e-02
```

**4.b.** Run *Simulator3* 10 times with a stopping criterion of $P$ = 100000 at each run to estimate all performance parameters and their 90% confidence intervals when $\lambda$ = 1800 pps, $C$ = 10 Mbps, $f = 10^4$ Bytes (~10 KBytes) and the BER is $b = 10^{-5}$. Results (recall that these are simulation results):

```
PacketLoss (%)          = 6.19e+00 +- 2.79e-01
Av. Packet Delay (ms)   = 4.20e+00 +- 8.25e-02
```

```
Max. Packet Delay (ms) = 9.18e+00 +- 1.09e-02
Throughput (Mbps)      = 8.19e+00 +- 8.02e-02
```

**4.c.** Consider the connection characterized by $C$ = 10 Mbps, $f = 10^7$ Bytes (~10 MBytes) and BER $b$ = 0. Run both *Simulator2* and *Simulator3*, 10 times each, with a stopping criterion of $P$ = 100000 at each run to estimate all performance parameters when $\lambda$ = 1500, 1600, 1700, 1800, 1900 and 2000 pps. Present the results of both simulators in a single bar chart for each performance parameter. Take conclusions on the impact of both packet arriving models on the different performance parameters and justify the obtained results.

**4.d.** Consider the packet rate $\lambda$ = 1800 pps and the connection characterized by $C$ = 10 Mbps and BER $b$ = 0. Run both *Simulator2* and *Simulator3*, 10 times each, with a stopping criterion of $P$ = 100000 at each run to estimate all performance parameters when $f$ = 2500, 5000, 7500, 10000, 12500, 15000, 17500 and 20000 Bytes. Present the results of both simulators in a single bar chart for each performance parameter Take conclusions on the impact of both packet arriving models on the different performance parameters and justify the obtained results.

**4.e.** Repeat experiment **4.c** considering now that the connection has a BER of $b = 10^{-5}$. Justify the obtained results comparing them with the simulation results of experiment **4.c** and take conclusions on the impact of both packet arriving models on the different performance parameters.

**4.f.** Repeat experiment **4.d** considering now that the connection has a BER of $b = 10^{-5}$. Justify the obtained results comparing them with the simulation results of experiment **4.d** and take conclusions on the impact of both packet arriving models on the different performance parameters.

## Appendix A – Performance of a connection with bit error rate and modeled as a *M*/*G*/1 queuing system

Consider a packet switching connection of capacity $C$ (in bps) which introduces a bit error rate $b$ and is modeled by a *M*/*G*/1 queueing system. The packet arrival rate in $\lambda$ (in packets/second) and packet sizes are $B_1$, $B_2$, …, $B_n$ (in Bytes), with probabilities $p_1$, $p_2$, …, $p_n$, respectively.

***Packet Loss (PL):***

The probability of each packet size $B_i$ being sent without errors is:

$$P_i = (1 - b)^{8 \times B_i}$$

So, the packet loss (in %) is the weighted sum of the packet loss probability of each packet size, where the weights are the probabilities of the packet sizes:

$$PL = 100\% \times \sum_{i=1}^{n} p_i \times (1 - P_i)$$

***Average Packet Delay (APD):***

In a *M*/*G*/1 queueing system, the average queueing delay for all packets is:

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

where $E[S]$ is the average packet transmission time and $E[S^2]$ is the average square of the packet transmission time:

$$E[S] = \sum_{i=1}^{n} p_i \times \frac{8 \times B_i}{C} \qquad\qquad E[S^2] = \sum_{i=1}^{n} p_i \times \left(\frac{8 \times B_i}{C}\right)^2$$

Then, the average packet delay of each packet size $B_i$ (if sent without errors) is the sum of its average queueing delay and its transmission time:

$$W_i = W_q + \frac{8 \times B_i}{C}$$

So, the average packet delay is the average delay of all packets that are sent without errors:

$$APD = \frac{\sum_{i=1}^{n}(p_i \times P_i \times W_i)}{\sum_{i=1}^{n}(p_i \times P_i)}$$

***Total Throughput (TT):***

The total throughput is the sum of the throughput of the packets that are sent without errors for each packet size $B_i$:

$$TT = \sum_{i=1}^{n}(p_i \times P_i \times \lambda \times (8 \times B_i))$$