# Chapter Three

# Simulations of Some Active Queue Management Methods

## 3.1 Evaluation of RED, DRED, GRED, ARED and BLUE

In this chapter, a comparison between five AQM methods is made. These methods are RED [46], DRED [11], GRED [50], ARED [49] and BLUE [39, 43], in terms of several performance measures, including mean queue length ( $mql$ ), throughput ( $T$ ), average queueing delay ( $D$ ), and the total of overflow packet loss and dropping probabilities ( $P_{Loss}$ ). The goals of this comparison are to decide which of the methods offer 1) the most satisfactory performance measure results, 2) The fewest number of lost and dropped packets using the overflow loss probability ( $P_L$ ) and packet dropping probability ( $D_P$ ). The above AQM techniques were implemented in a Java on a 1.66 Centrino 1024 MB RAM machine. This chapter is organised as follows: Subsection 3.1.1 introduces the simulation details for the AQM methods such as the arrival and departure processes and the number of router buffers. The evaluation of the AQM methods based on the performance measures ($mql$, $T$, $D$, $P_{Loss}$) is presented in Subsection 3.1.2. Subsection 3.1.3 shows the $P_L$ and $D_P$ results for the compared AQM methods. The statistical analysis of the AQM methods for ten runs is given in Subsection 3.1.4. Finally, Section 3.2 is the chapter summary.

### 3.1.1 The Simulation Details

The simulation details include the types of arrival and departure processes used in each AQM method. Moreover, the scheduling policy for the packets and the number of router buffers specified for each AQM method simulated. The packets arrive to and depart from a single router buffer separately (not in a batch). The process that models the arriving packets is a Bernoulli process and the simulations of the AQM methods have been built using a discrete-time approach. Also, the packets depart from the router buffer with geometrically distributed service times. The queueing discipline in all the simulations is FCFS. The single router buffer for the AQM methods simulated is shown diagramatically in Figures (3.1-3.3). In particular, Figure 3.1 represents the single router buffer for either DRED or BLUE. The RED and ARED router buffer is shown in Figure 3.2. Finally, the GRED router buffer is depicted in Figure 3.3.

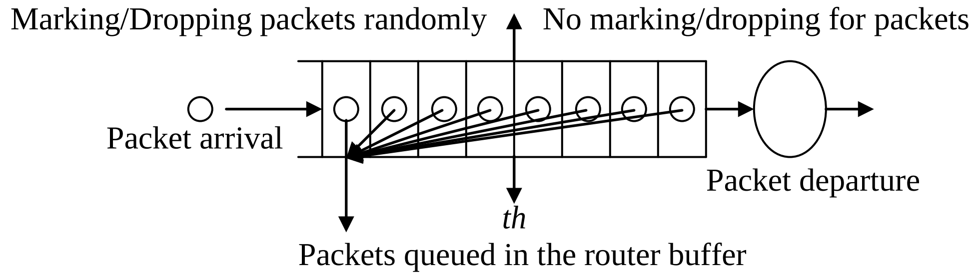


Figure 3.1: The single router buffer for either the DRED or BLUE.

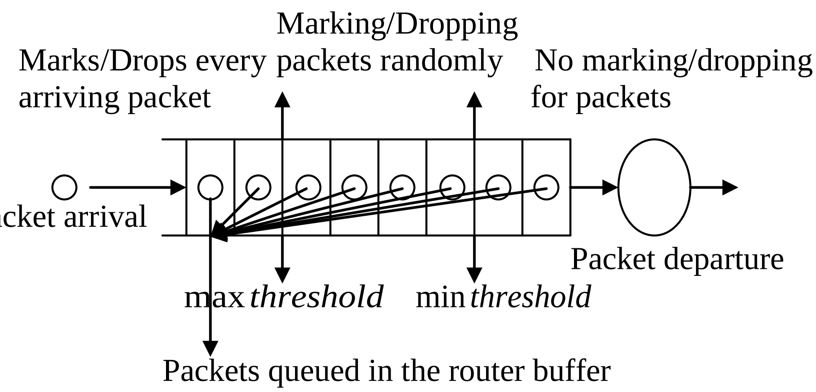


Figure 3.2: The single router buffer for either the RED or ARED.

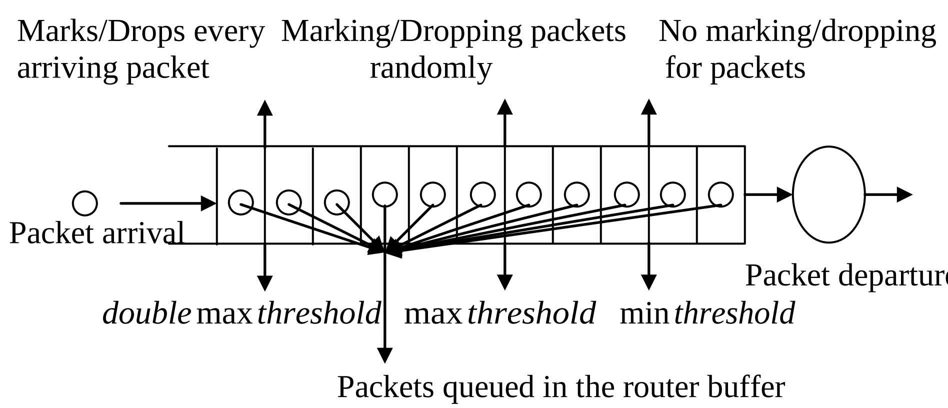


Figure 3.3: The single router buffer for GRED.

In order to validate the RED simulation in this thesis, the throughput and average queueing delay performance measures have been chosen as validation measures. The throughput and average queueing delay results of the RED simulation are compared with their corresponding results in the proposed RED-Linear analytical model which will be presented in Subsection 6.5.2 in this thesis (For more details see Subsection 6.5.2). Figures [3.4 and 3.5] display the throughput and average queueing delay results for the RED simulation and analytical model. The RED simulation and model have been implemented within a Java environment. The parameters of the RED simulation and model were set as in Table 3.1. In Table 3.1 the simulation's $D_{\max}$ parameter is equivalent to $\left(\frac{\alpha 1-\alpha 2}{\alpha 1}\right)$ in the model, which is the maximum dropping probability. These were both set to the same values in order to operate the simulation and model under an

Table 3.1: The setting parameters of the RED simulation and model.

| Parameter | RED simulation and model |
|---|---|
| Probability of packet arrival ( $\alpha 1$ ) | 0.18-0.93 |
| Probability of packet arrival ( $\alpha 2$ ) | 0.1 |
| Probability of packet departure ( $\beta$ ) | 0.5 |
| Router buffer capacity | 20 |
| $\min threshold$ | 3 |
| $\max threshold$ | 9 |
| qw | 0.1 |
| $D_{\max}$ | $\left(\frac{\alpha 1-\alpha 2}{\alpha 1}\right)$ |
| Number of slots | 2000000 |

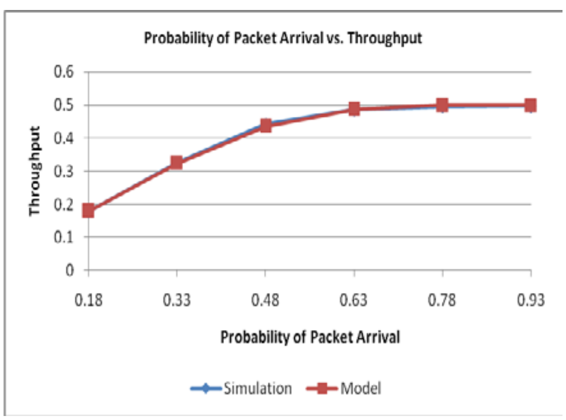


Figure 3.4: Throughput vs. $\alpha 1$.

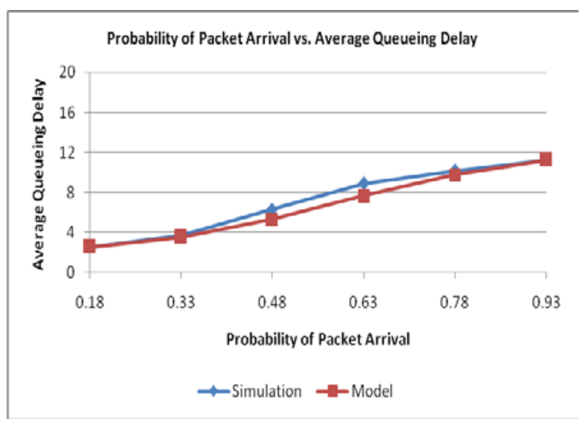


Figure 3.5: Average queueing delay vs. $\alpha 1$.

equivalent set of conditions. It is noted in Figures 3.4 and 3.5 that the throughput and average queueing delay results in both RED simulation and model are similar. This therefore gives a confidence that the simulator used to produce the performance measure results in the thesis is operating correctly. It also suggests that the model might be used as a good approximation for the RED simulation.

### 3.1.2 Performance Evaluation of RED, GRED, ARED, DRED and BLUE

The parameters of the RED, GRED and ARED have been set as in Table 3.2, whereas the DRED and BLUE parameters were set as in Table 3.3.

Table 3.2: The parameters for the RED, GRED and ARED algorithms in Section 3.1.2.

| Parameter | RED and GRED | ARED |
|---|---|---|
| Probability of packet arrival | 0.18-0.93 | 0.18-0.93 |
| Probability of packet departure | 0.5 | 0.5 |
| Router buffer capacity | 20 | 20 |
| $\min threshold$ | 3 | 3 |
| $\max threshold$ | 9 | 9 |
| qw | 0.002 | 0.002 |
| $D_{\max}$ | 0.1 | 0.1 |
| Number of slots | 2000000 | 2000000 |
| $d1$ | | 0.9 |
| Time interval | | 0.5 |

Table 3.3: The parameters for the DRED and BLUE algorithms in Section 3.1.2.

| Parameter | DRED | BLUE |
|---|---|---|
| Probability of packet arrival | 0.18-0.93 | 0.18-0.93 |
| Probability of packet departure | 0.5 | 0.5 |
| Router buffer capacity | 20 | 20 |
| $threshold$ | 9 | 12 |
| $D_{init}$ | 0.05 | 0.05 |
| Number of slots | 2000000 | 2000000 |
| C (t) | 1 | |
| $\varepsilon$ | 0.00005 | |
| qw | 0.002 | |
| $freeze\_time$ | | 0.01 |
| $P_{inc}$ | | 0.00025 |
| $P_{dec}$ | | 0.000025 |

In Table 3.2 the $\min threshold$ was set to a small value since the router buffer size is small. The $\max threshold$ has been set to triple $\min threshold$ as in [49] in order to achieve a higher throughput performance. Both queue weight ( qw ) and maximum dropping probability value ($D_{\max}$) parameters were set as in [46]. The parameters of the amount removed from the $D_{\max}$ ($d1$) and Time interval have been configured as in [49]. Moreover in the above tables, the probability of packet arrival was set to different values; half of them are lower than the probability of packet departure and the rest are larger. These varying values for the probability of packet arrival aim to identify the performance measure results both before and after congestion situations arise. The probability of packet departure has been set to 0.5 and the buffer size was set to a value of 20 packets in order to detect the congestion for small buffer sizes. The number of slots used in the experiments for the AQM methods was set to 2000000 to give accurate performance measure results and also to incorporate a warm-up period which terminates when it is detected that the system has reached a steady state. In Table 3.3 the parameters of DRED method (Indication congestion threshold ($threshold$), fixed unit of time (C (t)), system control parameter ($\varepsilon$), qw and initial packet dropping probability ($D_{init}$)) have been tuned to values as in [11]. The $D_{init}$ and the lowest time period between two successive $D_p$ adjustments ($freeze\_time$) parameters in the BLUE method were set to values as in [39, 43]. The rest of BLUE's parameters (certain level ($threshold$), the amount which $D_p$ should be increased ($P_{inc}$) and the amount which $D_p$ should be decreased ($P_{dec}$)) have been set to values as follows: the *threshold* was set to 0.6 of the buffer size [122] and both $P_{inc}$ and $P_{dec}$ parameters to values the same as in [24].

The performance measures versus packet arrival probability for the AQM methods compared are obtained after the system reached to a steady state. Each AQM algorithm simulation has been run ten times each run with a different seed for the random number generator, in order remove possible bias in the performance measure results and to produce confidence intervals for the performance measures. The mean of the ten runs for every performance measure at a specific probability of packet arrival was taken and these results are given in Figure [3.6-3.9]. Figures 3.6, 3.7, 3.8 and 3.9 illustrate the behaviour of the performance measures with the packet arrival probability. In particular, Figure 3.6 shows $mql$ versus packet arrival probability, Figure 3.7 displays $T$ versus packet arrival probability, Figure 3.8 demonstrates $D$ versus packet arrival probability and Figure 3.9 exhibits $P_{Loss}$ versus packet arrival probability.

It is observed in Figures 3.6 and 3.8 that all considered AQM methods present similar $mql$ and $D$ results when the probability of packet arrival is either 0.18 or 0.33. This is because the probability of packet arrival is lower than the probability of packet departure. Moreover, at these values for the probability of packet arrival mostly no congestion is present, and this indicates the similarity of the AQM method results with reference to the $mql$ and $D$. On the other hand, when the probability of packet arrival is increased to be near the probability of packet departure, i.e. 0.48, a light congestion is noted. Thus, the DRED method gives the smallest $mql$ and $D$ results. Therefore the DRED method sustains its $mql$ and $D$ results better than BLUE, RED, GRED and ARED methods. Also, the BLUE method produces $mql$ and $D$ results smaller than the RED, GRED and ARED methods since it maintains its $mql$ and $D$ at lower values than the corresponding results in the RED, GRED and ARED methods. The RED, GRED and ARED methods produce similar $mql$ and $D$ results when the probability of packet arrival is equal to 0.48 or 0.63.

When the congestion situation is increased such as when the probability of packet arrival value is larger than that of the probability of packet departure, the DRED method generates the most satisfactory $mql$ and $D$ results since the $mql$ and $D$ results are the smallest. The BLUE method follows the DRED method by achieving the second best $mql$ and $D$ results since it's results lower than that of RED, GRED and RED methods. DRED and BLUE give lower $mql$ and $D$ results than the others under heavy congestion because they drop packets more aggressively by using instantaneous queue length as a congestion measure. This result in a smaller $mql$ and hence a lower $D$. In cases where the probability of packet arrival is increased to be equal to 0.78 or 0.93, the GRED method outperforms both the RED and ARED methods with regard to $mql$ and $D$ results due to the fact that its generated $mql$ and $D$ results are smaller than those of RED and ARED. The RED and ARED methods offer similar $mql$ and $D$ results when the probability of packet arrival is equal to 0.78 or 0.93.

Figures 3.7 and 3.9 show that all AQM methods produce similar $T$ and $P_{Loss}$ results whether the probability of packet arrival is lower or larger than the probability of packet departure (whether there is congestion or not). Figure 3.7 displays that when the probability of packet arrival is below the probability of packet departure, the $T$ results for the AQM methods increase as long as the probability of packet arrival increases. However, if congestion occurs (the probability of packet arrival is larger than the probability of packet departure) then the $T$ results obtained for the AQM methods stabilise at the probability of packet departure. Figure 3.9 reveals that all the compared methods drop and lose packets ($P_{Loss}$) at similar rates.

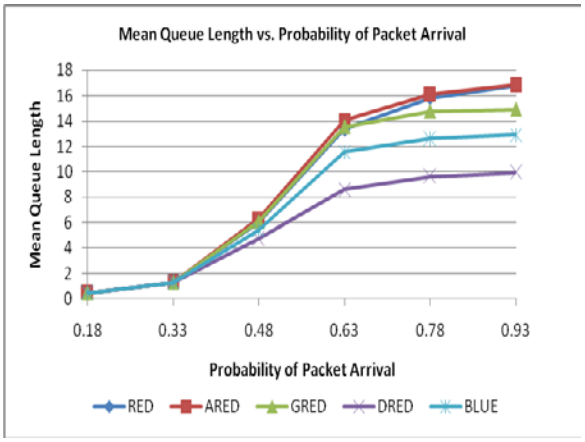


Figure 3.6: $mql$ vs. probability of packet arrival.

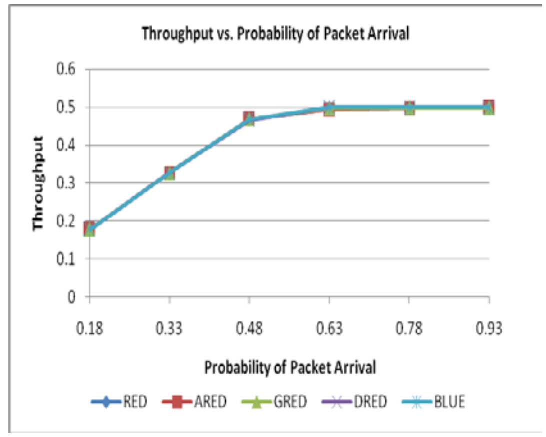


Figure 3.7: $T$ vs. probability of packet arrival.

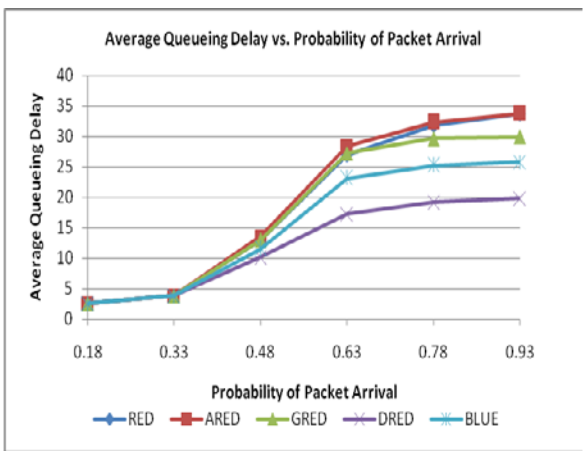


Figure 3.8: $D$ vs. probability of packet arrival.

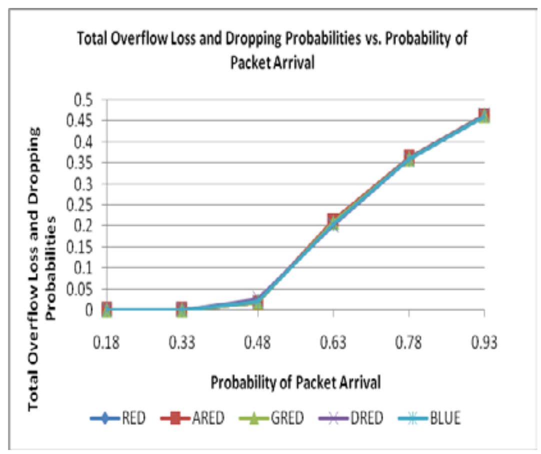


Figure 3.9: $P_{loss}$ vs. probability of packet arrival.

### 3.1.3 The Performance of the Overflow Loss and Dropping Probabilities

This subsection presents a comparison between the AQM techniques with respect to the overflow packet loss probability $(P_L)$ and packet dropping probability $(D_P)$ to identify which technique loses and drops fewer packets at its router buffer with reference to the packet arrival probability. The packet loses is due to buffer overflow. The parameters of the AQM techniques are set up as in Subsection 3.1.2.

Figures 3.10-3.11 depict the $P_L$ and $D_P$ results versus the probability of packet arrival for the considered AQM techniques, respectively. The results of $P_L$ and $D_P$ are obtained after the system is reached to a steady state. Moreover, every AQM algorithm simulation is run ten times through changing the seed in order to present a statistical analysis for the $P_L$ and $D_P$ results. Specifically, each value for the probability of packet arrival is run ten times through changing the seed in order to present a statistical analysis for the $P_L$ and $D_P$ results (For more details see Subsection 3.1.4). The ten run mean results of the $P_L$ and $D_P$ in the AQM methods compared are shown in Figures 3.10-3.11, respectively.

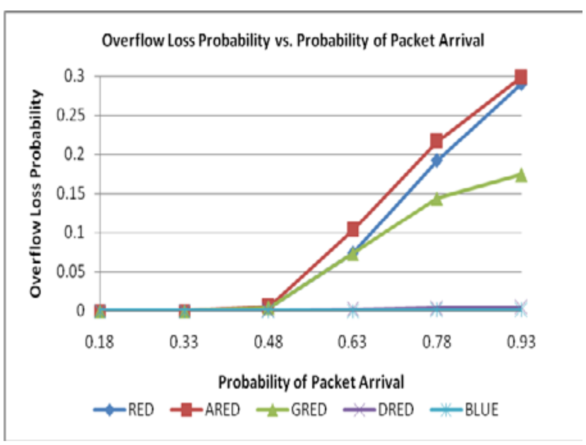


Figure 3.10: $P_L$ vs. probability of packet arrival.

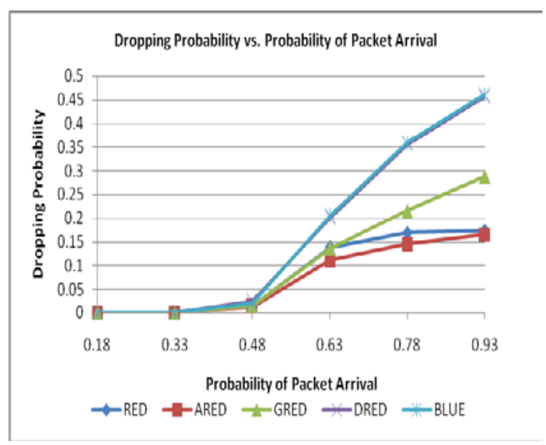


Figure 3.11: $D_p$ vs. probability of packet arrival.

Figures 3.10-3.11 show that all AQM techniques lose and drop similar amounts of packets when the probability of packet arrival is lower than the probability of packet departure. This is because there is either light congestion or no congestion at the router's buffers of the AQM techniques. Losing of packets is due to overflowing the routers buffers. Conversely, if the probability of packet arrival becomes higher than the probability of packet departure (existence of congestion), the DRED and BLUE techniques lose similar amounts of packets ( $P_L$ ) and these $P_L$ results are lower than those of the RED, GRED and ARED techniques since their router's buffers overflow less. Moreover, the RED and GRED techniques produce similar $P_L$ results when the probability of packet arrival is equal to 0.63 and these results are better than the $P_L$ results for the ARED technique. However, if the probability of packet arrival increases to be 0.78, the GRED technique becomes better than RED and ARED in terms of the $P_L$ results (it loses fewer packets) since the GRED router buffer overflows less than those of RED or ARED. Also, at this value for the probability of packet arrival, the RED loses slightly fewer packets than ARED. If the packet arrival probability is equal to 0.93, a high congestion situation is shown, and in this situation the GRED remains better than both the RED and ARED, in that it has lower packet loss ( $P_L$ ), where the $P_L$ is computed due to overflowing a router buffer. On the other hand, the RED and ARED lose a similar amount of packets ( $P_L$ ) due to their router's buffers overflowing at similar times.

After analysing Figure 3.11, it is shown that when the probability of packet arrival is higher than the probability of packet departure, a congestion situation is apparent. In this situation, both DRED and BLUE methods drop larger number of packets than the RED, GRED and ARED methods because their router buffers become overflow at times lower than the RED, GRED and ARED. When the probability of packet arrival reaches 0.63, the

ARED technique drops fewer amounts of packets ($D_p$) than either the RED or GRED techniques because the ARED's router buffer overflows more often than the buffers of RED or GRED. Furthermore, the RED and GRED techniques drop similar amounts of packets when the packet arrival probability is equal to 0.63. When the packet arrival probability increases to 0.78, ARED still offers the lowest dropping probability result ($D_p$), whereas RED becomes better than the GRED due to the GRED router buffer overflowing than that of RED. Finally, if the probability of packet arrival is increased to 0.93 (a value that reflects the highest congestion situation of all the values considered), both RED and ARED drop similar amounts of packets which are less than GRED and this is since the RED and ARED buffers overflow more often than that of GRED.

### 3.1.4 Statistical Analysis of the RED, GRED, ARED, DRED and BLUE

This subsection presents a statistical analysis for the performance measures of the AQM methods considered. The statistical analysis is obtained from the ten runs at each value of probability of packet arrival. So, every performance measure such as $T$ is obtained from ten results obtained from the ten runs. The data set for each performance measure can be represented by the ten run results. The data sets of the performance measures are analysed using statistics in order to describe them. To describe data sets, many statistical measurements can be applied, for instance mean, dispersion measurements (variance ($\sigma^2$), standard deviation ($\sigma$)) [32] and 95% confidence intervals (CI) [32] among others. In this subsection four statistical measurements are used to analyse the performance measure data sets, these are mean, $\sigma^2$ , $\sigma$ and 95% CI. The mean is performed to calculate the arithmetic mean for a specific data set. Both $\sigma^2$ and $\sigma$ are used to describe a dispersion of data for a specific data set from the mean of that data set. The 95% CI produces lower and upper limits for the mean, closer differences for the lower and upper limits for the CI from the mean provide more accurate mean result. 95% CI implies a 95% chance that the CI contains the mean of an individual run. The mean, $\sigma^2$ , $\sigma$ and 95% CI are given in equations (3.1-3.4), respectively.

$$\text{mean} = \frac{1}{m}\sum_{i=1}^{m} x_i \; , \qquad (3.1)$$

where $x_i$ is the value of the performance measure for run $i$, $i$ = 1, 2, … , $m$ (and $m$ = 10 runs in this work).

$$\sigma^2 = \frac{1}{m}\sum_{i=1}^{m}(x_i - mean)^2 \qquad (3.2)$$

$$\sigma = \sqrt{\sigma^2} \qquad (3.3)$$

From equation (3.2), $\sigma^2$ denotes the average of the squared differences from the mean.

Whereas equation (3.3) shows that $\sigma$ represent the square root of the $\sigma^2$.

$$95\ \%\ \text{CI} = \text{mean} \pm 1.96\sqrt{\sigma^2/m} \; , \qquad (3.4)$$

where $\sigma^2$ is the variance.

This subsection introduces statistical analysis for two AQM methods from all AQM methods compared. One is implemented based on average queue length and the other implemented based on the instantaneous queue length. These AQM methods are BLUE and RED; the BLUE has been selected because it has performance measure results lower than the DRED method, especially for the $mql$ and $D$. The RED is chosen since RED is the most popular AQM method and was implemented based on average queue length. The statistical measurements (mean, $\sigma^2$, $\sigma$ and 95% CI) with regard to the packet arrival probability for the BLUE and RED are displayed in Tables[3.4-3.15]. In particular, the performance measure means ($mql, T, D, P_L, D_p, P_{Loss}$) for the BLUE method versus the probability of packet arrival are exhibited in Tables [3.4-3.9], respectively. In addition, Tables [3.4-3.9] show the statistical analysis results (mean, $\sigma^2$, $\sigma$ and 95% CI, upper limit, lower limit) for the BLUE algorithm. In terms of the RED method the performance measure means and the statistical analysis results are given in Tables [3.10-3.15].

Table 3.4: Mean $mql$ vs. probability of packet arrival with statistical analysis for the BLUE method.

| BLUE Method | | | | | | |
|---|---|---|---|---|---|---|
| Probability of Packet Arrival | 0.18 | 0.33 | 0.48 | 0.63 | 0.78 | 0.93 |
| Mean $mql$ | 0.457 | 1.2790 | 5.4289 | 11.578 | 12.607 | 12.918 |
| $\sigma^2$ | 2.640E-06 | 0.0003 | 0.058 | 0.001 | 4.461E-05 | 2.644E-06 |
| $\sigma$ | 0.001 | 0.018 | 0.242 | 0.037 | 0.006 | 0.001 |
| 95% CI | 0.001 | 0.011 | 0.150 | 0.023 | 0.004 | 0.001 |
| Upper Limit | 0.458 | 1.2902 | 5.5793 | 11.601 | 12.611 | 12.919 |
| Lower Limit | 0.456 | 1.2678 | 5.2786 | 11.555 | 12.603 | 12.917 |

Table 3.5: Mean $T$ vs. probability of packet arrival with statistical analysis for the BLUE method.

| BLUE Method | | | | | | |
|---|---|---|---|---|---|---|
| Probability of Packet Arrival | 0.18 | 0.33 | 0.48 | 0.63 | 0.78 | 0.93 |
| Mean $T$ | 0.1787 | 0.327 | 0.4690 | 0.499 | 0.5 | 0.5 |
| $\sigma^2$ | 3.4694E-07 | 1.946E-06 | 5.385E-06 | 1.48606E-08 | 0 | 0 |
| $\sigma$ | 0.0005 | 0.001 | 0.002 | 0.000121904 | 0 | 0 |
| 95% CI | 0.0003 | 0.0008 | 0.001 | 7.55555E-05 | 0 | 0 |
| Upper Limit | 0.1790 | 0.328 | 0.4705 | 0.499 | 0.5 | 0.5 |
| Lower Limit | 0.1783 | 0.326 | 0.4676 | 0.499 | 0.5 | 0.5 |

Table 3.6: Mean $D$ vs. probability of packet arrival with statistical analysis for the BLUE method.

| BLUE Method | | | | | | |
|---|---|---|---|---|---|---|
| Probability of Packet Arrival | 0.18 | 0.33 | 0.48 | 0.63 | 0.78 | 0.93 |
| Mean $D$ | 2.560 | 3.9030 | 11.5713 | 23.1622 | 25.2150 | 25.836 |
| $\sigma^2$ | 0.0001 | 0.002 | 0.213 | 0.004 | 0.0001 | 1.057E-05 |
| $\sigma$ | 0.010 | 0.047 | 0.462 | 0.070 | 0.013 | 0.003 |
| 95% CI | 0.006 | 0.029 | 0.286 | 0.043 | 0.008 | 0.002 |
| Upper Limit | 2.566 | 3.9322 | 11.8579 | 23.2060 | 25.2233 | 25.838 |
| Lower Limit | 2.554 | 3.8737 | 11.2846 | 23.1184 | 25.2067 | 25.834 |

Table 3.7: Mean $P_L$ vs. probability of packet arrival with statistical analysis for the BLUE method.

| BLUE Method | | | | | | |
|---|---|---|---|---|---|---|
| Probability of Packet Arrival | 0.18 | 0.33 | 0.48 | 0.63 | 0.78 | 0.93 |
| Mean $P_L$ | 0 | 0 | 2.13E-05 | 1.02E-04 | 2.13E-04 | 3.18E-04 |
| $\sigma^2$ | 0 | 0 | 1.632E-10 | 1.904E-10 | 4.657E-10 | 7.523E-10 |
| $\sigma$ | 0 | 0 | 1.277E-05 | 1.379E-05 | 2.158E-05 | 2.742E-05 |
| 95% CI | 0 | 0 | 7.919E-06 | 8.553E-06 | 1.337E-05 | 1.700E-05 |
| Upper Limit | 0 | 0 | 2.92E-05 | 1.11E-04 | 2.26E-04 | 3.35E-04 |
| Lower Limit | 0 | 0 | 1.34E-05 | 9.35E-05 | 2.00E-04 | 3.01E-04 |

Table 3.8: Mean $D_p$ vs. probability of packet arrival with statistical analysis for the BLUE method.

| BLUE Method | | | | | | |
|---|---|---|---|---|---|---|
| Probability of Packet Arrival | 0.18 | 0.33 | 0.48 | 0.63 | 0.78 | 0.93 |
| Mean $D_p$ | 0 | 0 | 0.019 | 0.204 | 0.3588 | 0.4619 |
| $\sigma^2$ | 0 | 0 | 1.096E-05 | 7.813E-06 | 1.601E-07 | 2.455E-07 |
| $\sigma$ | 0 | 0 | 0.003 | 0.002 | 0.0004 | 0.0004 |
| 95% CI | 0 | 0 | 0.002 | 0.001 | 0.0002 | 0.0003 |
| Upper Limit | 0 | 0 | 0.021 | 0.206 | 0.3590 | 0.4622 |
| Lower Limit | 0 | 0 | 0.017 | 0.202 | 0.3585 | 0.4616 |

Table 3.9: Mean $P_{Loss}$ vs. probability of packet arrival with statistical analysis for the BLUE method.

| BLUE Method | | | | | | |
|---|---|---|---|---|---|---|
| Probability of Packet Arrival | 0.18 | 0.33 | 0.48 | 0.63 | 0.78 | 0.93 |
| Mean $P_{Loss}$ | 0 | 0 | 0.019 | 0.204 | 0.3590 | 0.4623 |
| $\sigma^2$ | 0 | 0 | 1.101E-05 | 7.770E-06 | 1.541E-07 | 2.422E-07 |
| $\sigma$ | 0 | 0 | 0.003 | 0.002 | 0.0003 | 0.0004 |
| 95% CI | 0 | 0 | 0.002 | 0.001 | 0.0002 | 0.0003 |
| Upper Limit | 0 | 0 | 0.021 | 0.206 | 0.3592 | 0.4626 |
| Lower Limit | 0 | 0 | 0.017 | 0.202 | 0.3587 | 0.4619 |

Table 3.10: Mean $mql$ vs. probability of packet arrival with statistical analysis for the RED method.

| RED Method | | | | | | |
|---|---|---|---|---|---|---|
| Probability of Packet Arrival | 0.18 | 0.33 | 0.48 | 0.63 | 0.78 | 0.93 |
| Mean $mql$ | 0.457 | 1.279 | 6.082 | 13.367 | 15.8307 | 16.827 |
| $\sigma^2$ | 2.640E-06 | 0.0003 | 0.051 | 0.001 | 0.0028 | 0.004 |
| $\sigma$ | 0.001 | 0.018 | 0.226 | 0.035 | 0.0535 | 0.065 |
| 95% CI | 0.001 | 0.011 | 0.140 | 0.021 | 0.0332 | 0.040 |
| Upper Limit | 0.458 | 1.290 | 6.22 | 13.389 | 15.8639 | 16.868 |
| Lower Limit | 0.456 | 1.267 | 5.942 | 13.345 | 15.7975 | 16.787 |

Table 3.11: Mean $T$ vs. probability of packet arrival with statistical analysis for the RED method.

| RED Method | | | | | | |
|---|---|---|---|---|---|---|
| Probability of Packet Arrival | 0.18 | 0.33 | 0.48 | 0.63 | 0.78 | 0.93 |
| Mean $T$ | 0.178 | 0.327 | 0.468 | 0.496 | 0.4979 | 0.498 |
| $\sigma^2$ | 3.469E-07 | 1.946E-06 | 2.703E-06 | 4.496E-09 | 1.417E-09 | 3.273E-10 |
| $\sigma$ | 0.0005 | 0.001 | 0.001 | 6.705E-05 | 3.764E-05 | 1.809E-05 |
| 95% CI | 0.0003 | 0.0008 | 0.001 | 4.155E-05 | 2.333E-05 | 1.121E-05 |
| Upper Limit | 0.179 | 0.328 | 0.469 | 0.496 | 0.4979 | 0.498 |
| Lower Limit | 0.178 | 0.326 | 0.467 | 0.496 | 0.4979 | 0.498 |

Table 3.12: Mean $D$ vs. probability of packet arrival with statistical analysis for the RED method.

| RED Method | | | | | | |
|---|---|---|---|---|---|---|
| Probability of Packet Arrival | 0.18 | 0.33 | 0.48 | 0.63 | 0.78 | 0.93 |
| Mean $D$ | 2.560 | 3.903 | 12.973 | 26.924 | 31.7923 | 33.754 |
| $\sigma^2$ | 0.0001 | 0.002 | 0.198 | 0.005 | 0.0118 | 0.017 |
| $\sigma$ | 0.010 | 0.047 | 0.445 | 0.070 | 0.1089 | 0.131 |
| 95% CI | 0.006 | 0.029 | 0.276 | 0.043 | 0.0675 | 0.081 |
| Upper Limit | 2.566 | 3.932 | 13.250 | 26.967 | 31.8598 | 33.836 |
| Lower Limit | 2.554 | 3.873 | 12.697 | 26.880 | 31.7248 | 33.673 |

Table 3.13: Mean $P_L$ vs. probability of packet arrival with statistical analysis for the RED method.

| RED Method | | | | | | |
|---|---|---|---|---|---|---|
| Probability of Packet Arrival | 0.18 | 0.33 | 0.48 | 0.63 | 0.78 | 0.93 |
| Mean $P_L$ | 0 | 0 | 0.004 | 0.073 | 0.19187 | 0.290 |
| $\sigma^2$ | 0 | 0 | 1.768E-06 | 1.403E-06 | 5.435E-06 | 2.088E-05 |
| $\sigma$ | 0 | 0 | 0.001 | 0.001 | 0.0023 | 0.004 |
| 95% CI | 0 | 0 | 0.0008 | 0.0007 | 0.0014 | 0.002 |
| Upper Limit | 0 | 0 | 4.88E-03 | 7.43E-02 | 0.19332 | 0.293 |
| Lower Limit | 0 | 0 | 3.23E-03 | 7.28E-02 | 0.19043 | 0.287 |

Table 3.14: Mean $D_p$ vs. probability of packet arrival with statistical analysis for the RED method.

| RED Method | | | | | | |
|---|---|---|---|---|---|---|
| Probability of Packet Arrival | 0.18 | 0.33 | 0.48 | 0.63 | 0.78 | 0.93 |
| Mean $D_p$ | 0 | 0 | 0.015 | 0.138 | 0.169 | 0.173 |
| $\sigma^2$ | 0 | 0 | 5.789E-06 | 6.787E-07 | 4.557E-06 | 2.142E-05 |
| $\sigma$ | 0 | 0 | 0.002 | 0.0008 | 0.002 | 0.004 |
| 95% CI | 0 | 0 | 0.001 | 0.0005 | 0.001 | 0.002 |
| Upper Limit | 0 | 0 | 0.016 | 0.138 | 0.170 | 0.175 |
| Lower Limit | 0 | 0 | 0.013 | 0.137 | 0.168 | 0.170 |

Table 3.15: Mean $P_{Loss}$ vs. probability of packet arrival with statistical analysis for the RED method.

| RED Method | | | | | | |
|---|---|---|---|---|---|---|
| Probability of Packet Arrival | 0.18 | 0.33 | 0.48 | 0.63 | 0.78 | 0.93 |
| Mean $P_{Loss}$ | 0 | 0 | 0.019 | 0.211 | 0.361 | 0.3614 |
| $\sigma^2$ | 0 | 0 | 1.176E-05 | 1.471E-06 | 4.455E-07 | 4.680E-07 |
| $\sigma$ | 0 | 0 | 0.003 | 0.001 | 0.0006 | 0.0006 |
| 95% CI | 0 | 0 | 0.002 | 0.0007 | 0.0004 | 0.0004 |
| Upper Limit | 0 | 0 | 0.021 | 0.212 | 0.361 | 0.3618 |
| Lower Limit | 0 | 0 | 0.017 | 0.211 | 0.360 | 0.3610 |

It is noted in Tables [3.4-3.15] that the statistical results ($\sigma^2$, $\sigma$ and 95% CI, upper limit, lower limit) of the BLUE and RED methods are extremely small. This implies more accurate mean results for the performance measures. Also, this gives indication that the data dispersion of the data set for each performance measure from the mean is too small, for instance the confidence interval provides lower and upper limits for the mean, and this interval reveals how much there are differences from the mean. Tables [3.4-3.15] show narrower differences of lower and upper limits from the mean and these give further accurate results for the performance measure means. Moreover, the DRED, GRED and ARED methods also generate very small statistical analysis results, but they are not included in this chapter since the inclusion of both the BLUE and RED is deemed sufficient to illustrate things. Most of larger deviations in the performance measures for the AQM methods were generated when the probability of packet arrival was set to 0.48, although these results still quite small.

## 3.2 Chapter Summary

In this chapter, five popular AQM algorithms (RED, GRED, ARED, DRED and BLUE) have been implemented using a Java simulation to compare them with respect to different network performance measures ($mql$, $T$, $D$, $P_L$, $D_p$, $P_{Loss}$). The comparison of the AQM algorithms has been made for the same setting of parameter values as far as possible. Furthermore, the parameter of probability of packet arrival is the only variable parameter used and it has values set between 0.18 and 0.93. Half of the packet arrival probability values are thus at values lower than the probability of packet departure, whereas the rest are located at values larger than the probability of packet departure and these latter values result in a congestion situation. The fundamental goals for the experimentation were to identify the method(s) which 1) offer satisfactory performance measure results with reference to the values for probability of packet arrival, 2) overflow lose $(P_L)$ and drop

$(D_p)$ fewer packets regarding the values for probability of packet arrival and 3) present a statistical analysis (variance, standard deviation, 95% confidence interval) for the AQM methods based on the values for probability of packet arrival. The simulation results can be summarised as follows:

- All compared AQM algorithms give similar $mql$ and $D$ results when the probability of packet arrival is either 0.18 or 0.33. On the other hand, when light congestion occurs, i.e. the probability of packet arrival is equal to 0.48, the DRED algorithm offers $mql$ and $D$ results better than the results of the BLUE, RED, GRED and ARED algorithms. Also, the BLUE algorithm outperforms the RED, GRED and ARED algorithms concerning $mql$ and $D$ results. The RED, GRED and ARED algorithms produce similar $mql$ and $D$ results when the probability of packet arrival is equal to 0.48 or 0.63. The DRED algorithm offers the optimal $mql$ and $D$ results when the value of probability of packet arrival is larger than the value of the probability of packet departure (appearance of congestion). The BLUE algorithm outperforms the RED, GRED and ARED algorithms in terms of $mql$ and $D$ results when the probability of packet arrival is higher than the probability of packet departure. When the probability of packet arrival is equal to 0.78 or 0.93, both RED and ARED algorithms give similar $mql$ and $D$ results and these results are lower than that of the GRED algorithm.
- The AQM algorithms produce similar $T$ and $P_{Loss}$ results whatever the value of probability of packet arrival is. If the probability of packet arrival is lower than the probability of packet departure, then the $T$ results of the AQM algorithms increase as

long as the probability of packet arrival increases. On the other hand, if the probability of packet arrival is larger than the probability of packet departure, the $T$ result for the AQM algorithms will stabilise at the value of the probability of packet departure. All the AQM algorithms have similar dropping and losing packet results ( $P_{Loss}$ ).

- When the probability of packet arrival is smaller than the probability of packet departure, the compared AQM algorithms lose (due to overflow routers buffers ( $P_L$ )) and drop ( $D_p$ ) similar amount of packets.
- When the probability of packet arrival becomes larger than the probability of packet departure (occurrence of congestion), the DRED and BLUE algorithms lose a ( $P_L$ ) similar amount of packets and these amounts are lower than amounts of the RED, GRED and ARED algorithms.
- If the probability of packet arrival is 0.63, the RED and GRED algorithms offer similar $P_L$ results and these results are better than that of ARED. Further, the GRED outperforms either RED or ARED in terms of the $P_L$ when the probability of packet arrival is equal to 0.78. In addition, the RED presents $P_L$ results marginally better than the ARED when the packet arrival probability is 0.78. Finally, the GRED outperforms the RED and ARED according to $P_L$ when the probability of packet arrival is 0.93. Also, at this value for the packet arrival probability both the RED and ARED produce similar $P_L$ results.
- The DRED and BLUE drop the highest number of packets when the packet arrival probability is greater than the packet departure probability.

- The ARED drops fewer packets ($D_p$) than either RED or GRED when the packet arrival probability is 0.63. Moreover, both the RED and GRED drop similar amount of packets when the probability of packet arrival 0.63. The ARED obtains fewer $D_p$ result than either RED or ARED when the probability of packet arrival is 0.78 and the RED outperforms GRED with reference to the $D_p$ results at this value for the packet arrival probability. Lastly, The RED and ARED produce similar $D_p$ results when the probability of packet arrival is 0.93 and these results are better than the GRED's results.
- The simulations for the AQM algorithms considered give small deviation from the mean ($\sigma^2$, $\sigma$ and 95% CI, upper limit, lower limit) and this reflects results more accurate mean results for the performance measures.
- In the simulations for the AQM algorithms compared, the larger deviations in the mean occur when the probability of packet arrival was set to 0.48 although these deviations are still quite small.