

CHAPTER FIVE

RESULTS AND DISCUSSIONS

5.1 Introduction

This chapter presents the performance evaluation of the proposed methods (GB, GB–MMBP-2, and GBFL). The proposed methods are then compared with new and effective AQM methods based on the following performance measures: mql, T, D, PL, and DP. The evaluations aim to show which method provides better performance measures under all buffer states.

5.2 Performance Evaluation Results of GB

The performance measures of GB are collected after the simulation, and the results are compared with some of well-known and recent methods DGRED, ERED, Adaptive Max Threshold, and BLUE, which have been discussed extensively in Chapter Two. As mentioned in Chapters Three, Four, and Five, the results of all methods are collected when the system reaches a steady state with 10 runs, with each run using a different seed. We create different network scenarios in the router buffer (no congestion, light congestion, and heavy congestion) by setting the probability of packet arrival to different values. The parameters of packet arrival probability (α), packet departure probability (β), system capacity, and number of slots of all the compared methods are presented in the same manner as those of GB in Chapter Three. In addition, Th is set to 12, as recommended in BLUE (Feng et al., 2002), which represent 0.6 of the capacity. The minthreshold, maxthreshold, D_{\max} , and qw values

for DGRED, ERED, Adaptive Max Threshold, and RED are set to 3, 9, 0.1, and 0.002, respectively, as recommended in RED (Floyd & Jacobson, 1993). The doublemaxthreshold value is set to 18, as recommended in DGRED. Finally, freeze time, Pin, and Pde are set to 0.01, 0.00025, and 0.000025, respectively, as recommended in the BLUE method. Table 5.1 lists all the utilized parameters. The performance evaluation of the method simulations are based on the following performance measures: mql, T, D, PL, and DP.

Table 5.1: Parameter Settings for GB, DGRED, ERED, BLUE, Adaptive Max Threshold and RED Methods.

Parameter	GB	BLUE	DGRED, ERED, Adaptive Max Threshold
Probability of packet arrival	0.18-0.93	0.18-0.93	0.18-0.93
Probability of packet departure	0.5	0.5	0.5
Router buffer capacity	20	20	20
Queue weight	.....	.....	0.002
Number of slots	2000000	2000000	2000000
Minthreshold	.....	.....	3
Maxthreshold	.....	.....	9
DoubleMaxthreshold	.....	.....	18 (Just for DGRED)
Threshold	12	.....	.....
Freeze time	.....	0.01	.....
Pin	.....	0.00025	.....
Pde	.....	0.000025	.....

5.2.1 Threshold Selection

In this section the best value of the threshold is selected. The threshold selection uses two performance measures which are PL and DP in order to decide the best location for threshold value. The GB simulation runs several times, each run with different value of threshold. These values are {6, 8, 10, 12, and 14}. The

results are collected after the system reach steady state value. Figure 5.1 shows the comparison of threshold values in term of PL under different packets arrival probability. Subsequently, all the comparison GB when the threshold are equal {6, 8, 10, 12, and 14} are provide similar PL results when there is no congestion (packet arrival less than 0.63). Also, provides better performance measure when threshold equal 12 in both; heavy and light congestion than other set values of threshold. In addition, Figure 5.2 presents the DP of GB using different threshold values. The GB that uses 12 and 14 as a threshold values provides better DP value when there is no congestion compared with the GB that used the other value of threshold. In addition, it approximately provides similar DP results for all threshold values when light and heavy congestion occur.

As summary the optimal value of threshold value equals 12 in all cases of congestion status and this value is equal to 60% of the buffer size. This finding supports the setting of threshold value for original BLUE which GB was built based on it.

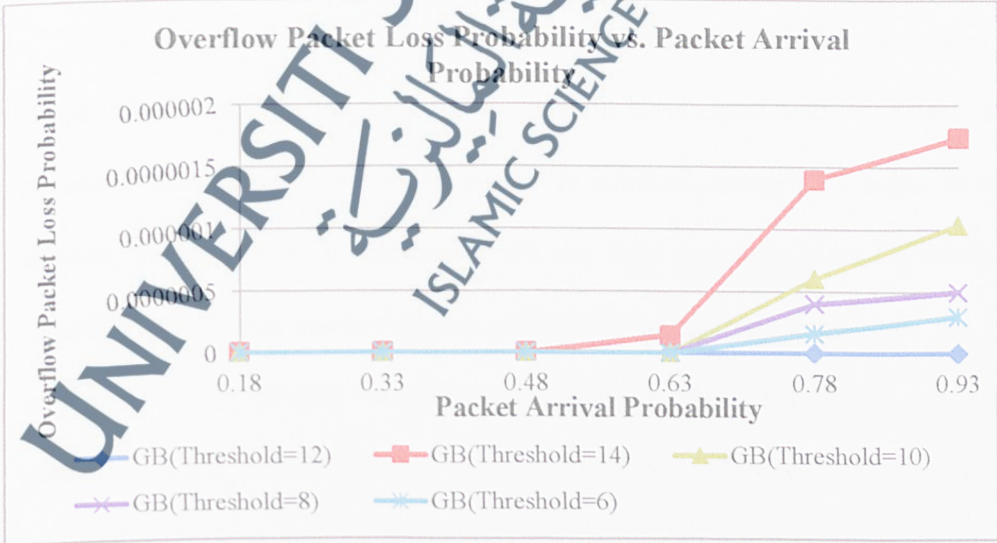


Figure 5.1: PL Result for Various Thresholds

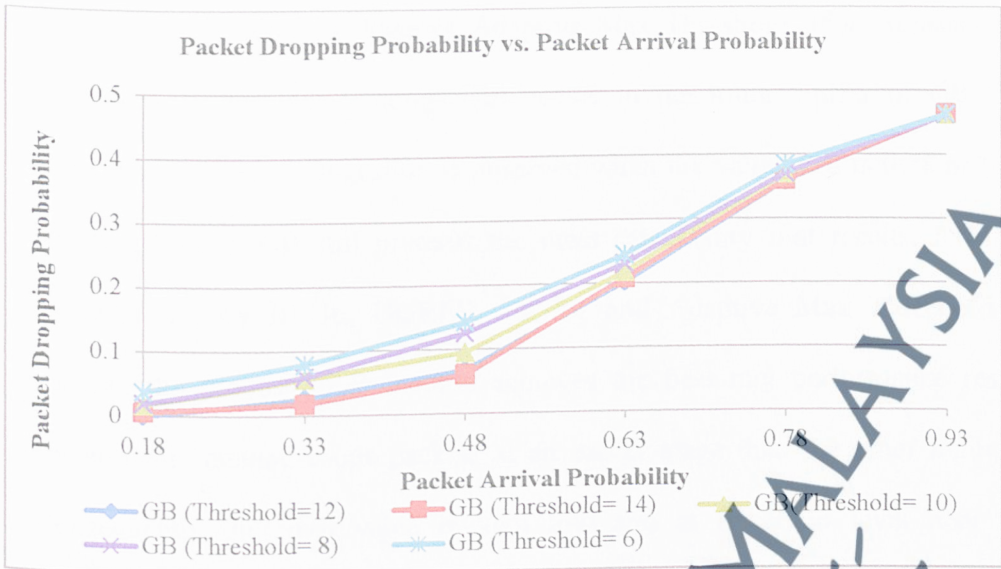


Figure 5.2: DP Result for Various Threshold

5.2.2 Mean Queue Length (mql)

As discussed in Chapter Three, mql is a good indicator of congestion, with the possibility of congestion being low if the mql value in the router buffer is low. The possibility of congestion in the router buffer increases as the mql value increases.

As presented in Figure 5.3, the mql values of all the compared and proposed methods are identical up to a certain level equal to 0.33. At this level, no congestion occurs in the router buffer. In addition, when the α value increases to 0.48, the proposed GB method offers the most satisfactory mql performance results because this method drops packets at an earlier stage than the other methods (BLUE, ERED, DGRED, and Adaptive Max Threshold), which have identical values in this case (α increases to 0.48). However, in case of light congestion (α increases to 0.63), GB still provides the most satisfactory mql results. ERED and BLUE have nearly the same mql results, which are better than those of Adaptive Max Threshold and DGRED. In addition, the mql results of

DGRED are better than those of Adaptive Max Threshold. If α increases and reaches 0.78, then heavy congestion occurs in the router buffer of GB. The occurrence of heavy congestion is observed when the value of α is 0.78 or 0.93. At these values, GB still presents the most satisfactory mql results, followed consecutively by BLUE, DGRED, ERED, and Adaptive Max Threshold. In general, the proposed GB method achieves the best mql performance results because this method drops packets at an earlier stage than the other methods. Consequently, the mql value is kept low and at a certain level near T_h , particularly when high congestion occurs. This condition will prevent the router queue from increasing its size and prevent the number of packets from reaching the capacity of the router buffer.

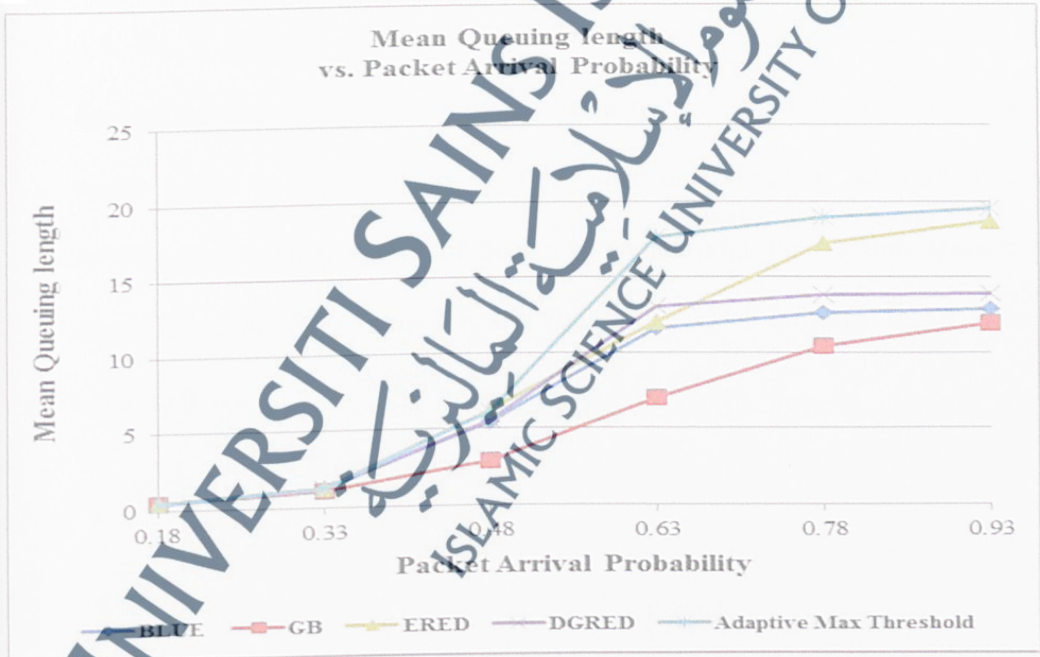


Figure 5.3: Performance Comparison among GB, BLUE, ERED, DGRED, and Adaptive Max Threshold Based on mql

5.2.3 Throughput (T)

Figure 5.4 illustrates the throughput (T)-based performance of the proposed and compared methods under different packet arrival probability values. The T results of the proposed and compared methods are stabilized with the value of packet departure probability (β) which is equal to 0.5 when congestion occurs in the router buffer. That is, if the value of α is less than the value of β , then the T results will increase for the proposed GB method and the compared methods. For instance, the GB method and the compared methods resulted in similar T results when α equal to 0.18, 0.33 and 0.48, the T results value at these packet arrival probabilities are 0.177, 0.32 and 0.44, respectively. This increase will continue until the value of α becomes equal to or greater than the value of β . The T results will stabilize at nearly 0.5 (nearly the value of β). In accordance with Equation 3.4, the T value is calculated as follows: $T = (1 - P[0]) * 0.5$, where $P[0]$ denotes the probability that no packet has arrived at the router buffer or that the router buffer is idle. Conversely, the router buffer cannot accommodate any arriving packet when congestion occurs given that it has no available space in this case. Hence, the $P[0]$ value is nearly equal to 0, which indicates that T is nearly equal to 0.5.

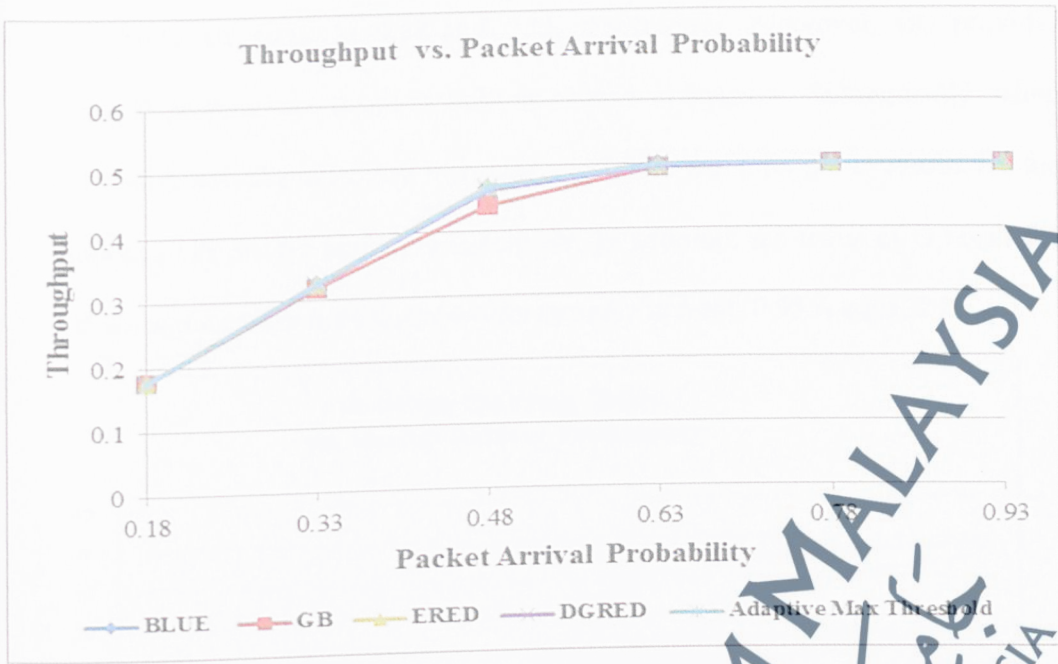


Figure 5.4: Performance Comparison among GB, BLUE, ERED, DGRED and Adaptive Max Threshold Based on T

5.2.4 Average Queuing Delay (D)

D is defined as the average waiting time for packets in the router buffer queue. Figure 5.5 represents the D performance of the proposed GB method and the other methods. The proposed method provides the best performance result in terms of D because the packets in the other methods require more time to depart compared with that in GB. In addition, D depends on mql, as compared in Figure 5.3. As previously mentioned, the mql of the proposed GB method is less than those of the compared methods. The relationship between mql and T is indicated in Equation 3.4, where this equation is Little's law: $D = mql/T$ (Woodward, 1993). The D-based results indicate that the router buffer of the proposed GB method will probably overflow within a shorter period than the router buffers of the compared methods.

All the proposed methods and the compared methods provide approximately similar D results equal to 2.5 and 3.5 when the packet arrival

probability are equal to 0.18 and 0.33, respectively. Moreover, GB provides better D performance result in light and heavy congestion. Subsequently, when the packet arrival probability increases up to 0.48 and 0.63 the D results for the proposed GB are 6.5 and 14, respectively. In addition, the value of D result for GB when the packet arrival probability increase to reach 0.93 is equal 24.

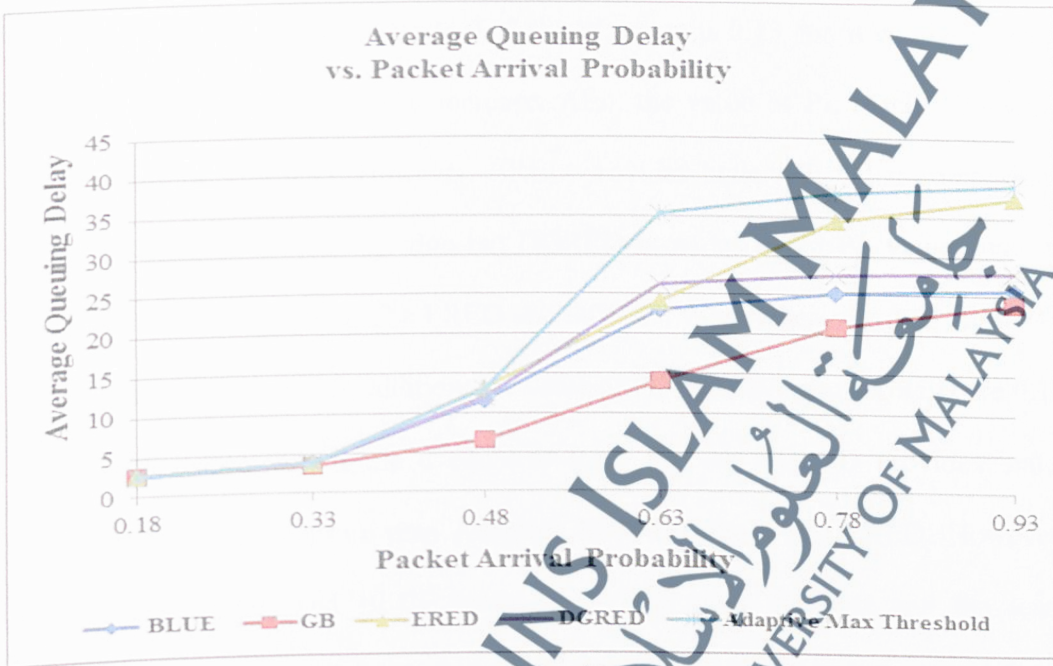


Figure 5.5: Performance Comparison among GB, BLUE, ERED, DGRED, and Adaptive Max Threshold Based on D

5.2.5 Overflow Packet Loss Probability

PL probability can be defined as the probability of losing packets due to router buffer overflow. The proposed GB method is also compared with the BLUE, ERED, DGRED, and Adaptive Max Threshold methods in terms of overflow PL probability.

In Figure 5.6, the proposed GB and BLUE methods slightly yield the best and the least PL performance results when heavy congestion occurs because the router buffer for GB overflows in less number of times compared with the router buffer for the other methods. GB prevents the size of the queue buffer from

building up, which consequently, prevents the buffer from overflowing better than the compared methods. PL is calculated using Equation 3.6. All the methods provide the same PL performance results in no congestion situations ($\alpha < \beta$). In addition, the Adaptive Max Threshold provides the worst PL values in light and heavy congestion ($\alpha > \beta$) comparing with the other methods. Subsequently, when the value of α increase up to 0.63 the PL value is 0.13 and it continue increasing as long as the value of α increase. Also, the value of PL reach 0.33 when the value of α is 0.93. However, ERED provides better PL value comparing with DGRED in light congestion but DGRED provides better PL value when heavy congestion occurred. The ERED and DGRED value when α is 0.63 are 0.014 and 0.05 respectively. In addition, the value of PL in ERED and DGRED are 0.19 and 0.03 respectively while α equal to 0.93. So, the DGRED provides better PL performance measure than Adaptive Max Threshold and ERED. However, the proposed GB and BLUE methods slightly yield the best and the least PL performance results when heavy congestion occurs comparing with other methods.

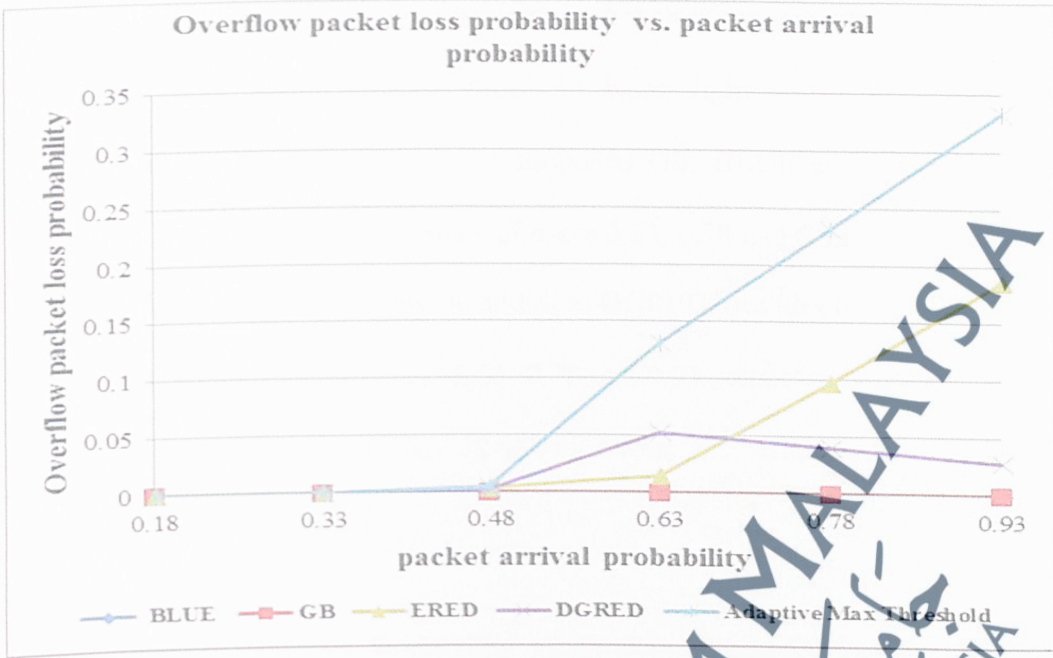


Figure 5.6: Performance Comparison among GB, BLUE, ERED, DGRED, and Adaptive Max Threshold Based on PL.

5.2.6 Packet Dropping Probability (DP)

DP represents the number of dropped packets when the router becomes congested and the probability of dropped packets before the router buffer becomes full. As shown in Figure 5.7, the DP result of GB is higher than those of the other methods because GB starts dropping packets earlier than the other methods. This condition indicates that the router buffer of the GB method overflows in less number of times compared with those of the other methods. Moreover, when heavy congestion occurs, GB, BLUE and ERED drop more packets than the other methods. In addition, when congestion does not occur, GB drops slightly more packets than the other methods.

In case of no congestion situation ($\alpha < \beta$) this case present when the values α are 0.18, 0.33 and 0.48 the proposed GB starts dropping packets earlier than the other methods the value of DP for GB are 0, 0.02 and 0.07 respectively and this value slightly greater than the other compared method. However, the proposed

GB, BLUE and ERED also drop more packet than other methods followed by DGRED then Adaptive Max Threshold when light and heavy congestion. Subsequently, the DP value of the proposed GB, BLUE and ERED provides similar DP values when the values of α are 0.63, 0.78 and 0.93 the DP value are 0.2, 0.35 and 0.46 respectively. In addition, DGRED provides 0.15, 0.32 and 0.43 when the values of α are equal 0.63, 0.78 and 0.93 respectively. Also, Adaptive Max Threshold provides 0.15, 0.32 and 0.43 when the values of α are equal 0.63, 0.78 and 0.93 respectively.

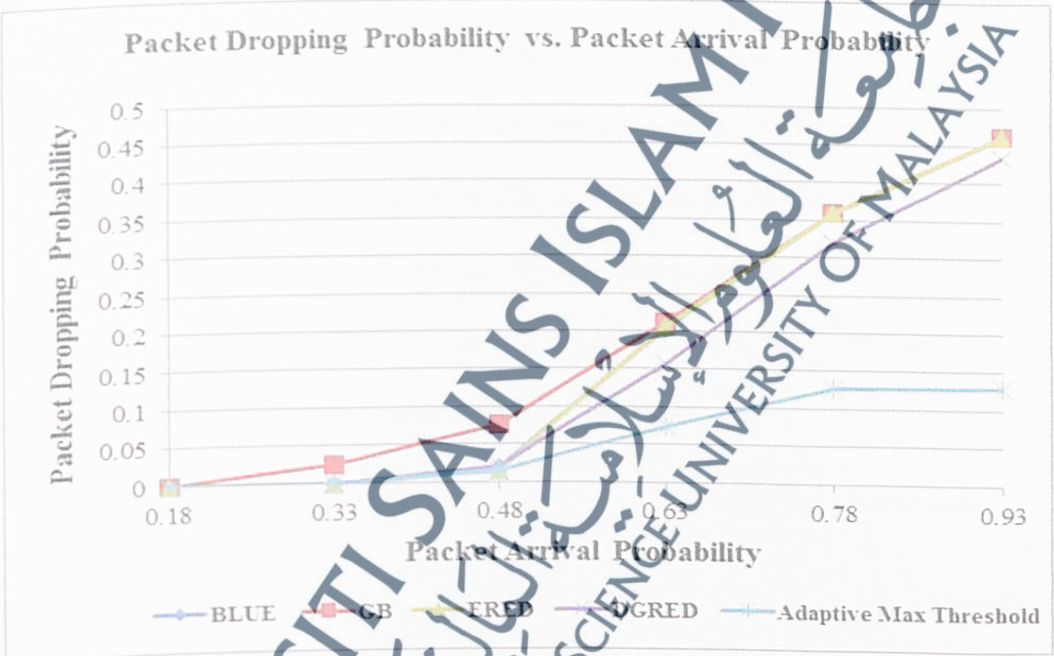


Figure 5.7: Performance Comparison among GB, BLUE, ERED, DGRED, and Adaptive Max Threshold Based on DP.

In general, when the values of packet arrival probability are 0.18 and 0.33, all the compared methods provide the same result given that congestion does not occur at these values. When the packet arrival probability value is 0.48, the mql, D, and PL measures of GB are the best because of the dynamic mechanism followed by this method. Moreover, DP is increased because the method starts

dropping packets early to prevent the overflow of the router buffer. In addition, all the compared methods provide the same T results. Finally, when the packet arrival probability values are 0.63, 0.78, or 0.93, light or heavy congestion occurs. In this case, the performance measures mql, D, and PL of GB will be the best compared with those of the other methods, and the T results will remain at 0.5.

5.3 Performance Evaluation of GB Simulation and the GB Analytical Model

The performance evaluation for GB simulation and the GB analytical model is conducted in the following subsections in terms of mql, D, T, PL, and DP. As previously mentioned, this evaluation aims to prove that GB simulation is working correctly. If the values of the performance measure results of GB simulation and the GB analytical model are similar, then GB simulation is validated to be operating correctly. As shown in Figures 5.8–5.12, GB simulation and the GB analytical model obtain similar performance measure results in terms of mql, D, T, PL, and DP. This finding confirms that GB simulation is working correctly.

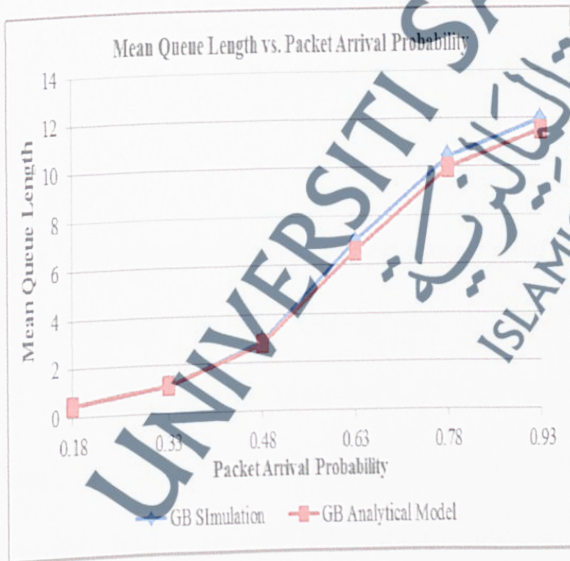


Figure 5.8: mql vs. Probability of Packet Arrival.

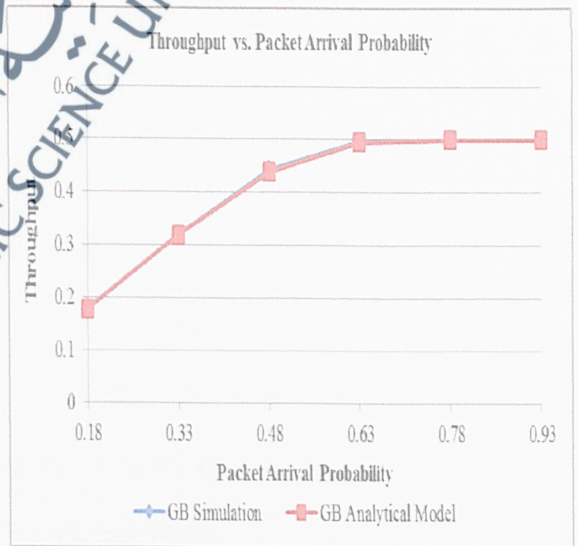


Figure 5.9: T vs. Probability of Packet Arrival

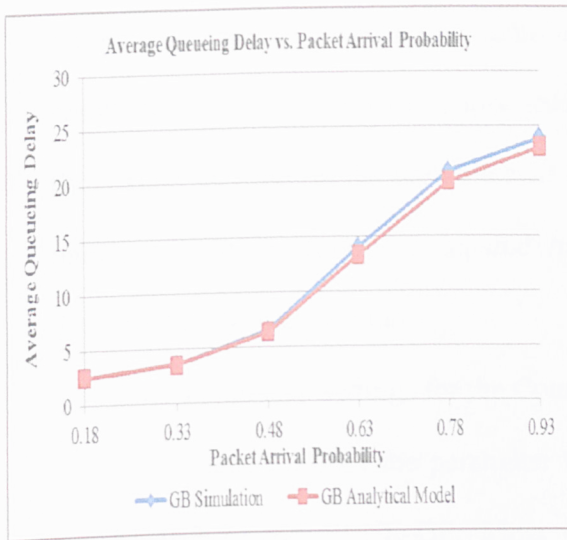


Figure 5.10: D vs. Probability of Packet Arrival.

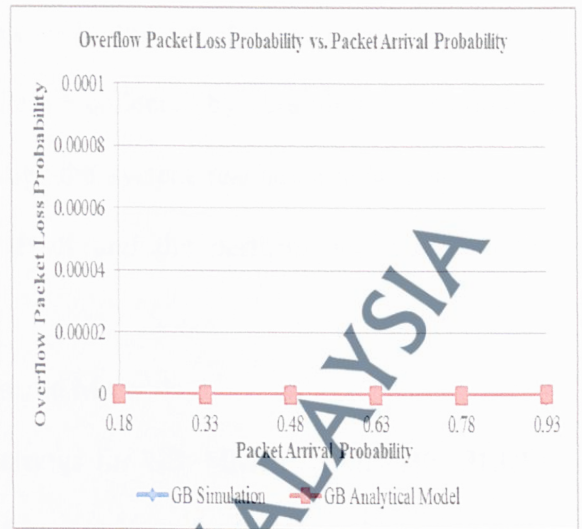


Figure 5.11: PL vs. Probability of Packet Arrival.

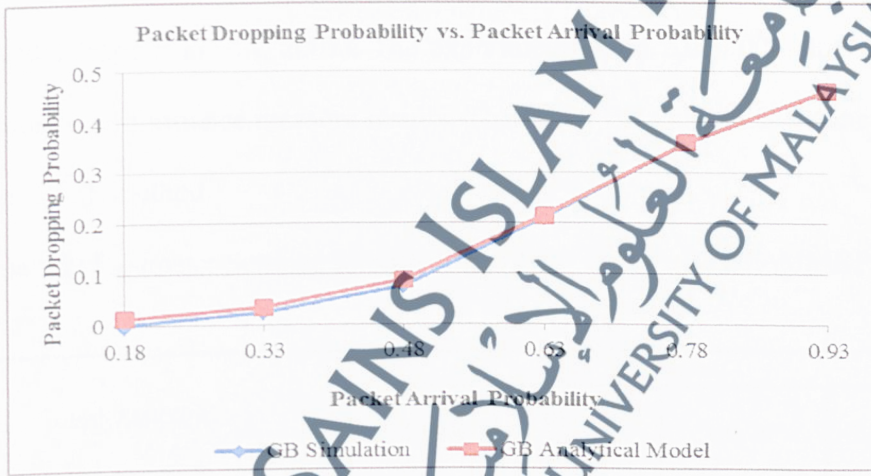


Figure 5.12: DP vs. Probability of Packet Arrival.

5.4 Performance Evaluation Results for GB-MMBP-2

In this section, GB-MMBP-2, GB-BP, BLUE-MMBP-2, and BLUE-BP are compared based on their performance measured through the following metrics: DP, mql, T, D, and PL. This comparison evaluates the performance of GB, which is represented using MMBP-2 under bursty and correlated traffic.

The comparison results of GB-MMBP-2, GB-BP, BLUE-MMBP-2, and BLUE-BP are obtained by implementing 10 runs with different seeds and by using

randomly generated numbers to eliminate bias toward the performance measure results for any run. The performance results are collected by obtaining the average of these runs. All the results are collected after the system reaches a steady state. The parameter settings for the compared methods and the performance measures are discussed in the next section.

5.4.1 Parameter Settings for the Compared Methods

Table 5.2 lists the parameter settings for GB–MMBP-2, GB–BP, BLUE–MMBP-2, and BLUE–BP. Most of the parameters are identical in all the methods. Buffer size is set to 20 packets to detect congestion for a small buffer (Abdel-Jaber et al. (b), 2007). The experiments used 2,000,000 slots to provide accurate performance measure results. The initial DP value is the same as that in the BLUE method.

Table 5.2: Parameter Settings for GB–MMBP-2, GB–BP, BLUE–MMBP-2, and BLUE–BP.

PARAMETER	Methods			
	BLUE-BP	BLUE-MMBP-2	GB-BP	GB-MMBP-2
Packet arrival probability for state 1 (α_0)	0.18–0.93	0.18–0.93	0.18–0.93	0.18–0.93
Packet arrival probability for state 2 (α_1)	-----	0.5	-----	0.5
Probability that the next packet will remain in state 1	-----	0.9	-----	0.9
Probability that the next packet will remain in state 2	-----	0.9	-----	0.9
Probability transition between state 1 and 2	-----	0.1	-----	0.1
Probability transition between state 2 and 1	-----	0.1	-----	0.1
Packet departure probability (β)	0.5	0.5	0.5	0.5
Router buffer capacity	20	20	20	20
Number of slots	2000000	2000000	2000000	2000000
Th	12	12	12	12
Freeze time	0.01	0.01	-----	-----
Pin	0.00025	0.00025	-----	-----
Pde	0.000025	0.000025	-----	-----
InitDP	0.05	0.05	0.05	0.05

The packet arrival probability for state 1 in GB–MMBP-2, GB–BP, BLUE–MMBP-2, and BLUE–BP is set to several values (i.e., 0.18–0.93). Each value can create either a congested or non-congested state. Thus, if the packet arrival probability value is less than that of the packet departure probability value, then no congestion will likely occur. However, if the packet arrival probability value is equal to or larger than that of the packet departure probability value, then congestion will likely occur. The values of packet arrival probability for state 2 in GB–MMBP-2 and BLUE–MMBP-2 are set to 0.5 to decrease the number of arriving packets, reduce congestion when high traffic load occurs, and avoid throughput deterioration (Guan et al., 2007).

BLUE–BP and GB–BP use BP, which only has one state, to model the arrival of packets. GB–MMBP-2 and BLUE–MMBP-2 use MMBP-2, which have two distinct states as previously mentioned, and thus, each upcoming packet can either remain in the same state or transfer to the next state. The probability that a packet will remain in the same state is 0.9, whereas that for a packet transferring to the next state is 0.1 (Step 3 in the proposed GB–MMBP-2). The remaining parameters (i.e., T_h , D_{max} , p_{in} , p_{de} , and $inIDP$) are set to values provided in the BLUE method (Feng et al., 2002).

5.4.2 Mean Queue Length and Average Queuing Delay

Figures 5.13 and 5.14 respectively present the mql- and D-based performance of the compared methods versus the values of packet arrival probability. The mql and D results of GB–BP and BLUE–BP are marginally less than those of GB–MMBP-2 and BLUE–MMBP-2 because the number of queued packets in GB–BP and BLUE–BP is less than that in GB–MMBP-2 and less than that in BLUE–MMBP-2 for all the methods. When the packet arrival probability

value is between 0.33 and 0.48, GB-BP and GB-MMBP-2 present similar mql and D results. These results are less than those of BLUE-BP and BLUE-MMBP-2 because GB-BP and GB-MMBP-2 drop more packets. When the packet arrival probability value is higher than or equal to 0.63, the proposed GB-MMBP-2 provides lower mql and D results than all the other methods because its current number of packets is smaller than those of the other methods even during heavy congestion. Moreover, GB-BP achieves lower mql and D results than BLUE-BP and BLUE-MMBP-2. In turn, BLUE-MMBP-2 provides lower mql and D results than BLUE-BP.

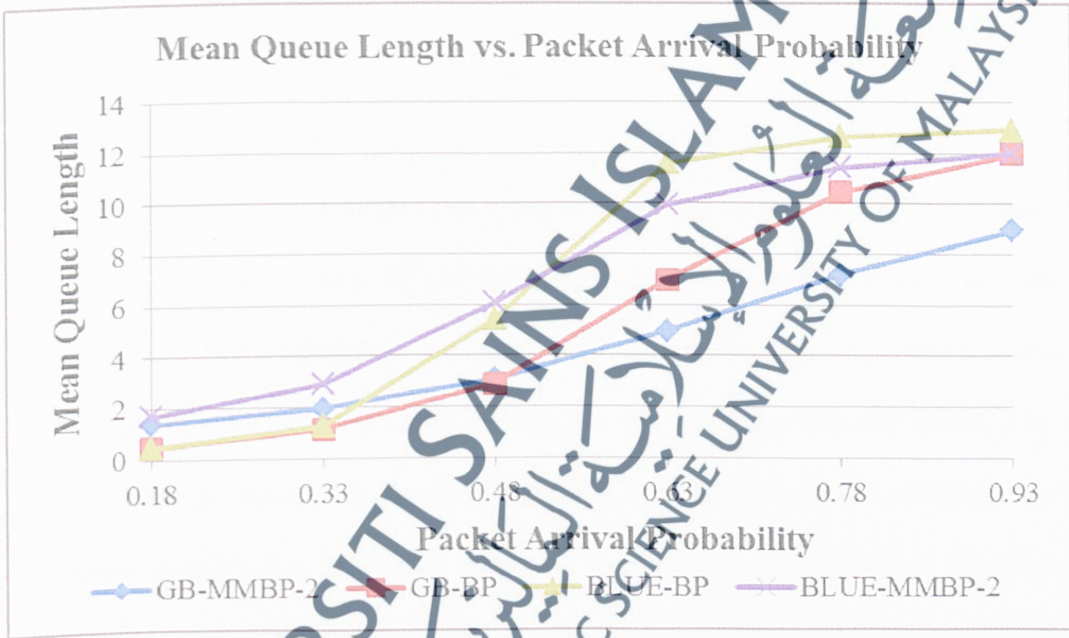


Figure 5.13: Performance Comparison among BLUE-BP, BLUE-MMBP-2, GB-BP, and GB-MMBP-2 Based on mql.

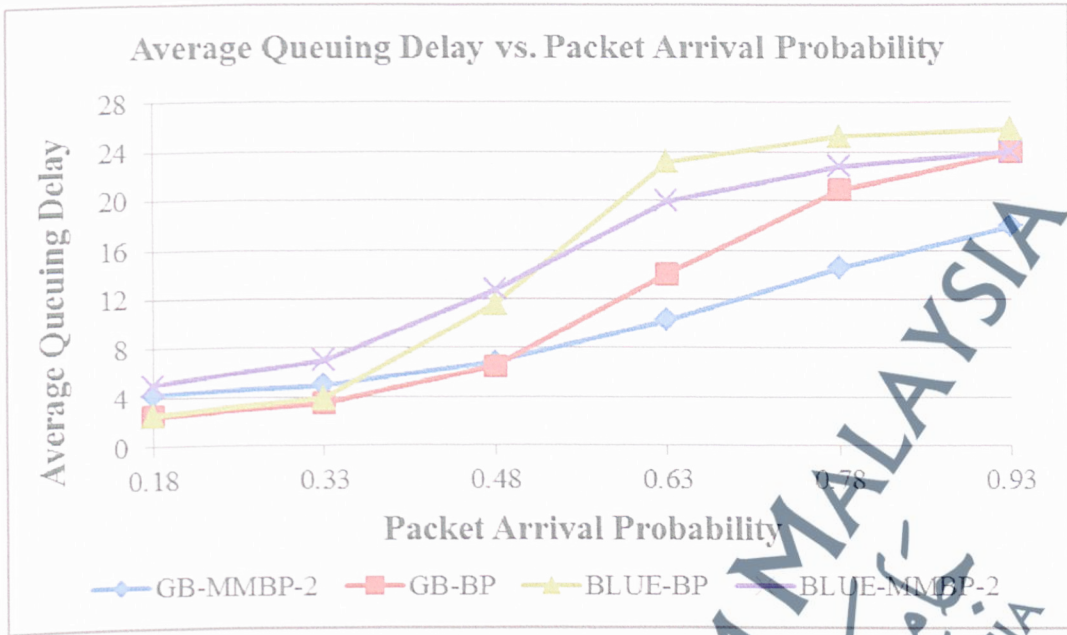


Figure 5.14: Performance Comparison among BLUE-BP, BLUE-MMBP-2, GB-BP, and GB-MMBP-2 Based on D

5.4.3 Throughput (T)

Figure 5.15 illustrates the T-based performance of GB-MMBP-2, GB-BP, BLUE-MMBP-2, and BLUE-BP under different packet arrival probability values. BLUE-MMBP-2 obtains higher T results than the other methods. Meanwhile, GB-MMBP-2 provides higher T results than GB-BP and BLUE-BP when the packet arrival probability value is 0.33 because BLUE-MMBP-2 serves more packets than the other methods. In addition, GB-MMBP-2 serves more packets than GB-BP and BLUE-BP. This result is attributed to the mql results at these arrival rates (no congested network status, and thus, the buffer can serve all the queued packets) being higher for BLUE-MMBP-2 than for the other methods because the number of packets in the router buffer is higher than that in the other methods. Meanwhile, mql results for GB-MMBP-2 are higher than GB-BP and BLUE-BP. GB-BP and BLUE-BP present similar T results at these rates. When the packet arrival probability value is higher than 0.33, all the compared methods

present similar T results, which are nearly equal to the packet departure probability value.

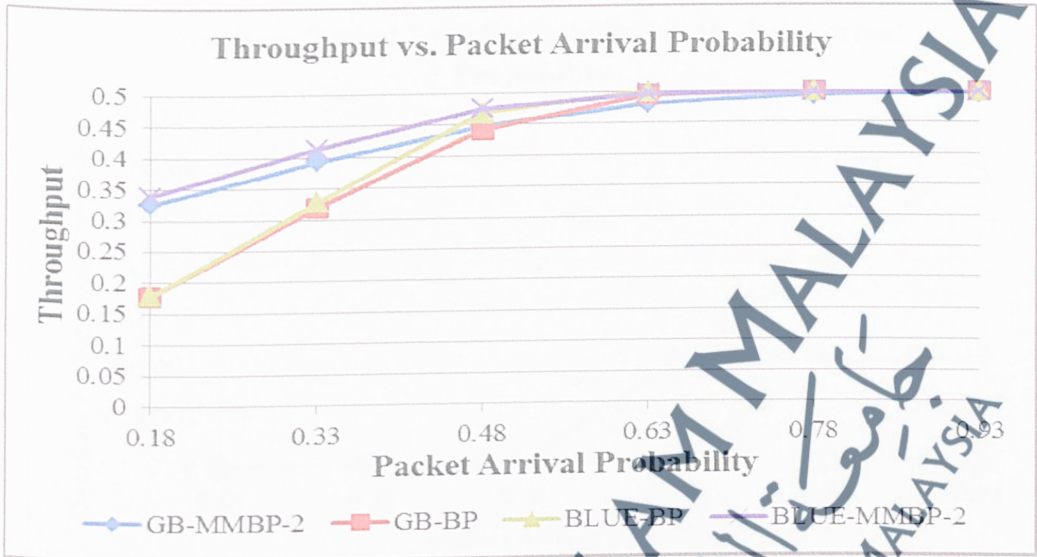


Figure 5.15: Performance Comparison among BLUE-BP, BLUE-MMBP-2, GB-BP and GB-MMBP-2 Based on T

5.4.4 Overflow Packet Loss Probability

GB-MMBP-2, GB-BP, BLUE-MMBP-2, and BLUE-BP are compared in terms of PL. Figure 5.16 shows that all the compared methods present similar PL results when the packet arrival probability value is 0.48 because their router buffers overflow at similar frequencies. All the compared methods, except for BLUE-BP, exhibit similar PL results when the packet arrival probability value is between 0.48 and 0.63 (i.e., occurrence of light congestion) because their router buffers overflow at a frequency that is less than that of BLUE-BP. GB-MMBP-2 and GB-BP yield the best and least PL performance results, respectively, when the packet arrival probability value is higher than or equal to 0.63 (i.e., occurrence of heavy congestion) because their router buffers overflow at a frequency that is less than those of BLUE-MMBP-2 and BLUE-BP. BLUE-

MMBP-2 loses fewer packets than BLUE-BP at these packet arrival probability values.

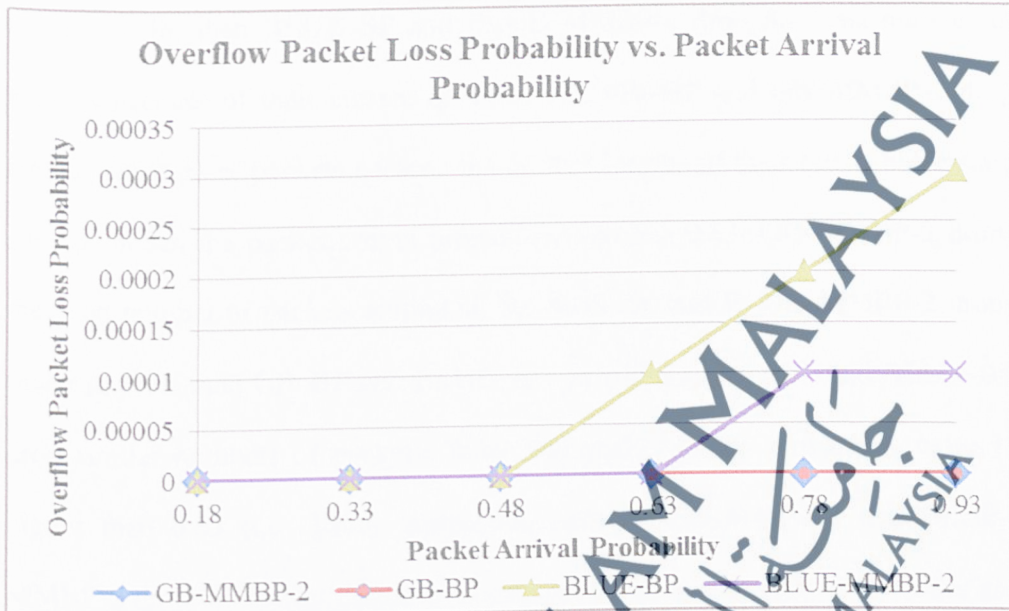


Figure 5.16: Performance Comparison among BLUE-BP, BLUE-MMBP-2, GB-BP, and GB-MMBP-2 Based on PL

5.4.5 Packet Dropping Probability (DP)

GB-MMBP-2, GB-BP, BLUE-MMBP-2, and BLUE-BP are compared in terms of DP. Figure 5.17 shows that BLUE-BP, BLUE-MMBP-2, and GB-BP provide similar DP results when the packet arrival probability value is 0.18. The results of these methods are lower than that of GB-MMBP-2 because MMBP can be transferred to state 2 (i.e., the packet arrival probability value is changed to 0.5), and thus, the number of arriving packets increases. Consequently, the number of queued packets increases, thereby increasing the DP value because GB-MMBP-2 calculates DP based on the status of q_l according to Equations 3.1 and 3.2. When the packet arrival probability value is 0.33, BLUE-BP and BLUE-MMBP-2 drop the least numbers of packets, and GB-BP drops fewer packets than GB-MMBP-2. This scenario can be attributed to the current q_l of

GB-MMBP-2 being the longest (but not fully) and that of GB-BP being longer than those of BLUE-BP and BLUE-MMBP-2. If the packet arrival probability value is 0.48, then BLUE-BP and BLUE-MMBP-2 drop the least number of packets because of their current ql. However, GB-BP and GB-MMBP-2 drop similar numbers of packets because the current lengths of their queue buffers are similar. When the packet arrival probability value is 0.63, GB-MMBP-2 drops the least number of packets among all the methods, and BLUE-MMBP-2 drops fewer packets than GB-BP and BLUE-BP. In addition, GB-BP and BLUE-BP drop similar numbers of packets. When the packet arrival probability value is higher than 0.63 (i.e., heavy congestion occurs), GB-MMBP-2 and BLUE-MMBP-2 drop the lowest numbers of packets because their current ql values are the shortest. GB-BP and BLUE-BP drop similar numbers of packets because their current ql values are nearly similar when heavy congestion occurs.

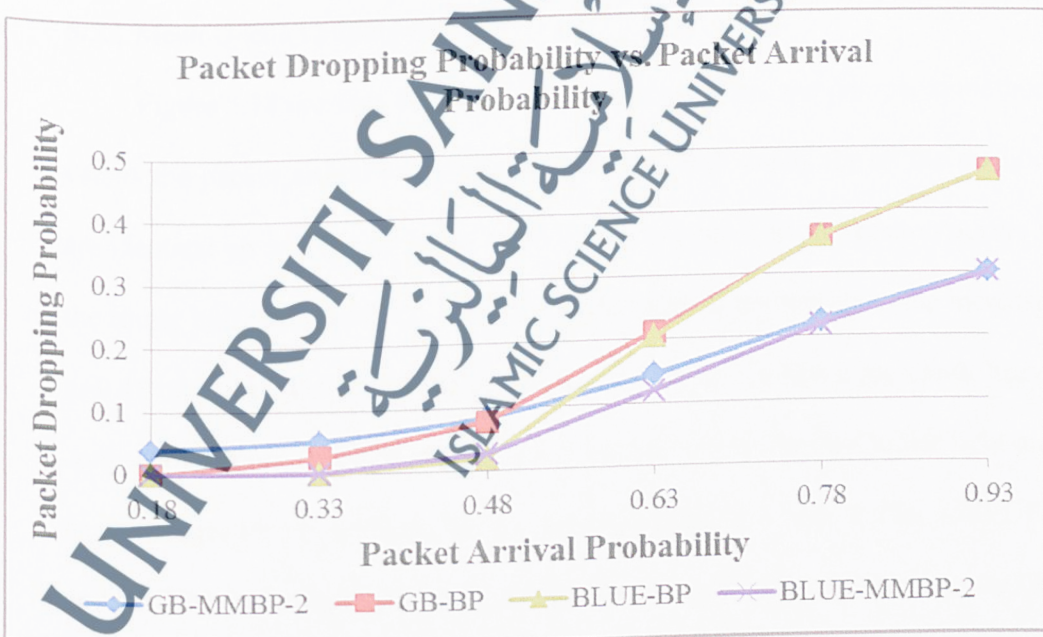


Figure 5.17: Performance Comparison among BLUE-BP, BLUE-MMBP-2, GB-BP, and GB-MMBP-2 Based on DP

5.5 Performance Evaluation for GBFL Results

This section discusses the performance evaluation for the proposed GBFL method and the compared methods (i.e., GREDFL, GB, and REDD1) based on the same performance metrics used for GB and GB-MMBP-2 under different values of α . The parameter settings for GBFL, GREDFL, GB, and REDD1 are set to the same values. Subsequently, α , buffer capacity, total time slot, and β are set to the same values as provided earlier. In addition, α is set to various values to cover all congestion cases (no congestion, light congestion, and heavy congestion). A small buffer capacity (20 packets) is used to detect congestion at a small buffer. The total time slot used in the simulations is 2,000,000 to provide accurate results and to ensure a sufficient warm-up period. The result of each simulation is computed after 10 runs, with each run using different seeds. The performance measure results are calculated when the system reaches a steady state.

5.5.1 Mean Queue Length (mql)

Figure 5.18 presents the mql results of the proposed and compared methods versus the packet arrival probability values. The mql results for all the methods are identical up to a certain level, i.e., 0.33. At this level, no congestion occurs in the router buffers. In addition, when the packet arrival probability value increases to 0.48 or higher (i.e., 63), light congestion is observed; when α increases, heavy congestion occurs. The GB method presents the best mql results under light and heavy congestion. In addition, GBFL achieves better mql results than GREDFL and REDD1 under light and heavy congestion. This result is attributed to the GB method dropping packets at an earlier stage than GREDFL and REDD1 when light and heavy congestion occur, thereby keeping the mql result low to prevent the router queue from building up its size and arriving packets from reaching the

capacity of the router buffer. Subsequently, the values of mql for GB when the values of α are 0.48, 0.63, 0.78 and 0.93 are 2.9, 7, 10.4, 12 respectively. The values of mql for GBFL when the values of α are 0.48, 0.63, 0.78 and 0.93 are 5, 11.9, 12.4, 12.4 respectively. GREDFL presents slightly lower performance results than REDD1 in terms of mql. The value of α are 0.48, 0.63, 0.78 and 0.93 are 7.3, 14.2, 14.4 and 14.8 respectively.

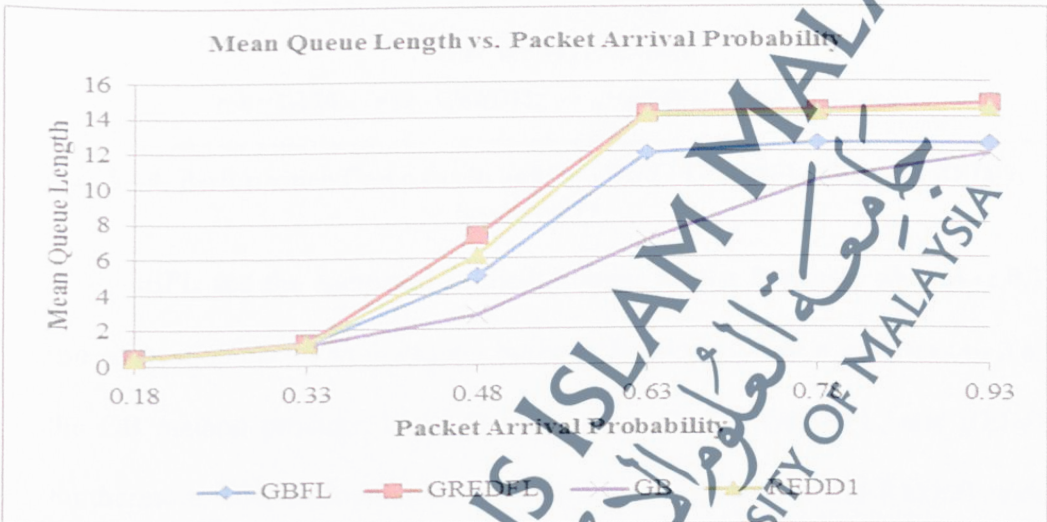


Figure 5.18: Performance Comparison among GBFL, GREDFL, GB, and REDD1 Based on mql

5.5.2 Average Queuing Delay (D)

Figure 5.19 presents the D results of GBFL, GB, GREDFL, and REDD1 under different α values.

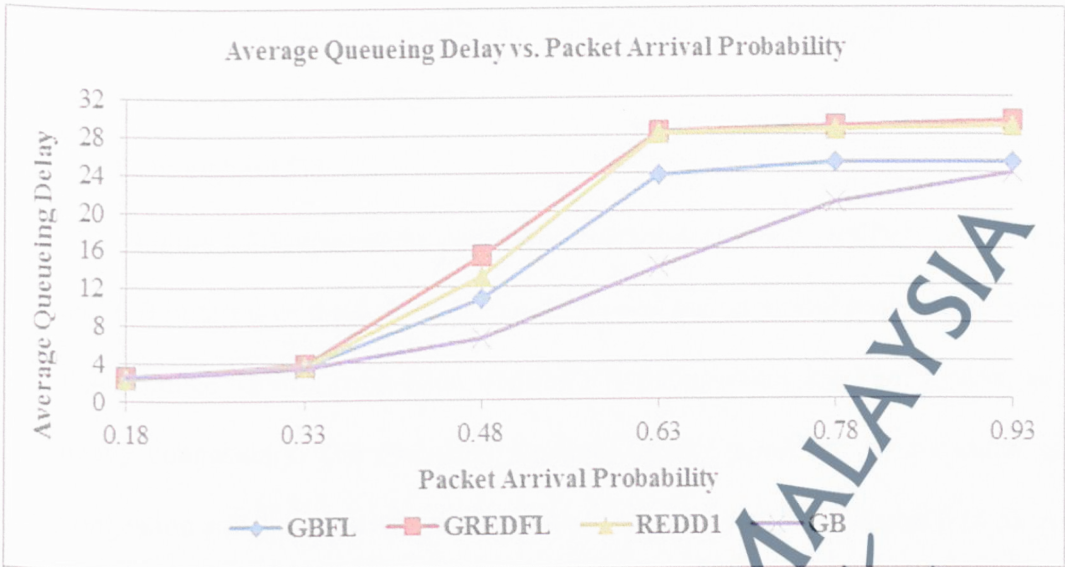


Figure 5.19: Performance Comparison among GBFL, GREDFL, GB, and REDD1 Based on D

GBFL and the compared methods exhibit similar D results when α is 0.33 (no congestion occurs in the router buffers). However, when α increases to 0.63, the GB method provides lower D values than GBFL, GREDFL, and REDD1. Furthermore, GBFL provides better D results than GREDFL and REDD1 under light congestion because GB and GBFL router buffers drop more packets than GREDFL and REDD1. The values of D result for GB, GBFL, GREDFL, and REDD1 when α increase to 0.63 is 14, 23.8, 28.5 and 28.2, respectively. Finally, when heavy congestion occurs (α value is equal to 0.78 or 0.93), GB and GBFL present lower D results than REDD1 and GREDFL. Subsequently, the values of D result for GB, GBFL, GREDFL, and REDD1 when α is equal to 0.78 is 20.9, 24.9, 28.8 and 28.4, respectively. Also, the value of D result for GB, GBFL, GREDFL, and REDD1 when α is equal to 0.93 are 23.9, 24.9, 28.8, 28.5 respectively. Moreover, at these α values, GB provides more satisfactory D results than GBFL because GB drops packets earlier than GBFL. At these α values, GREDFL and REDD1 exhibit similar D results because they provide

packets with similar mql results. In addition, the mql metric affects D. Thus, when mql is low, D is also low.

5.5.3 Throughput (T)

Figure 5.20 presents the performance outputs of GBFL, REDD1, GREDFL, and GB in terms of throughput (T) under several packet arrival probability values that produce varying congestion situations (no congestion, light congestion, and heavy congestion). The evaluated methods exhibit similar T results under all congestion situations except when α is 0.48, which is near the value of β (0.5). As shown in Figure 5.20, GB presents slightly lower T results when the packet arrival probability value is 0.48 because its router buffer overflows at a similar number of times as that of GBFL and fewer number of times as those of GREDFL or REDD1 when light congestion occurs.

The maximum value of T result should be 0.5, this value represents number of packets that have successfully passed through the router buffer per unit time. So the maximum value of T should be equal to the maximum value of β (0.5).

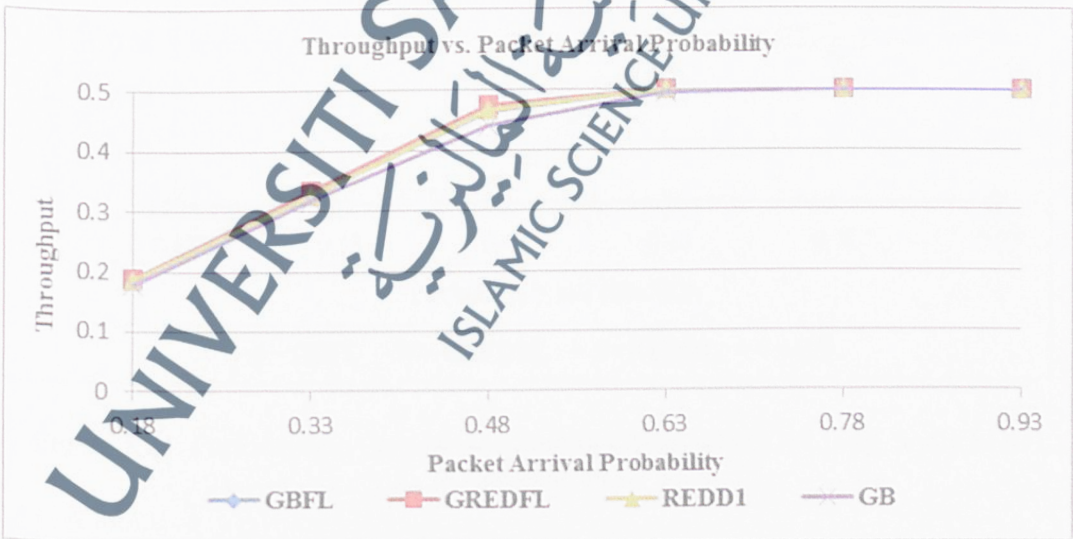


Figure 5.20: Performance Comparison among GBFL, GREDFL, GB, and REDD1 Based on T

5.5.4 Packet Loss Probability (PL)

Figure 5.21 presents a comparison among GB, GREDFL, REDD1, and GBFL in terms of overflow PL probability. This comparison aims to show the number of packets in the router buffer of these methods due to buffer overflow. All the compared methods provide similar PL results when α is 0.48 (no congestion occurs) because the router buffers of the methods overflow at similar numbers of times. GB and GBFL provide the best and worst PL results, respectively, when α is between 0.48 and 0.93 (light congestion and heavy congestion occur) because the router buffers of the GB and GBFL methods overflow at times that are less than those in other methods. That is, GB and GBFL stabilize the mql results at a specific level around T_h , which prevents the router buffer from building up its size at an early stage.

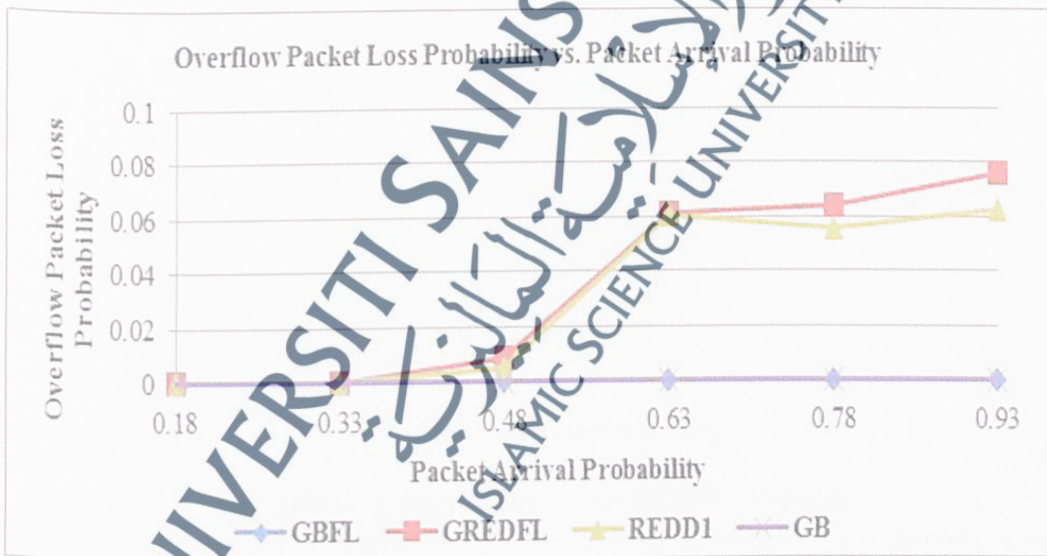


Figure 5.21: Performance Comparison among GBFL, GREDFL, GB, and REDD1 Based on PL

5.5.5 Packet Dropping Probability (DP)

Figure 5.22 presents a comparison among GB, GREDFL, REDD1, and GBFL in terms of packet DP. This comparison aims to illustrate the number of

dropped packets in these methods before the buffer becomes full. GBFL and GB drop more packets in their router buffers than GREDFL or REDD1 because the GBFL router buffer loses fewer packets due to overflow than the router buffers of GREDFL and REDD1. Furthermore, GB drops fewer packets than GBFL because the number of queued packets of GBFL is higher than that of GB. GREDFL and REDD1 drop similar numbers of packets because the lengths of their queue buffers are similar. For instance the value of DP for GB when light and heavy congestion occurs (0.63, 0.78 and 0.93) are 0.21, 0.35 and 0.46. In term of GBFL the values of DP are 0.29, 0.42, 0.54 when light and heavy congestion occurs (0.63, 0.78 and 0.93) respectively. However, GREDFL and REDD1 provide similar DP value when α are equal 0.63, 0.78 and 0.93 the DP value are 0.14, 0.3 and 0.4, respectively.

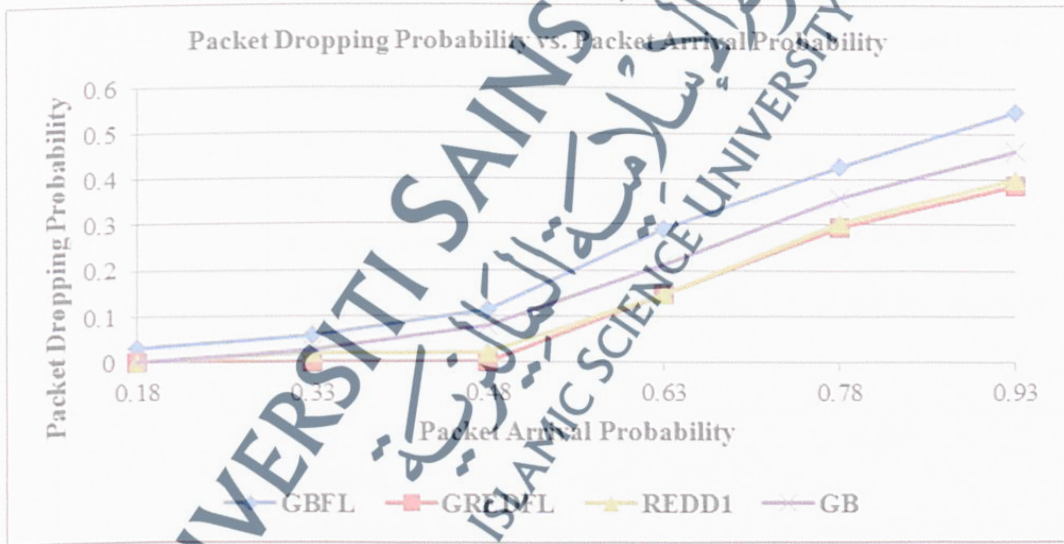


Figure 5.22. Performance Comparison among GBFL, GREDFL, GB, and REDD1 Based on DP.

5.6 Evaluation of Statistical Analyses

The following subsections provide the statistical analyses of the proposed methods (i.e., GB, GB-MMBP-2, and GBFL). Statistics is a means to extract

information from the obtained data. It can be defined as methods used to collect, organize, and analyze collected data (Clarke & Cooke, 2004). The following statistical analyses intend to provide a clear description of the output results of individual runs and to demonstrate how performance measure results spread from their mean. To conduct statistical analyses of the proposed methods, we use the following statistical measurements to represent the outputs: mean; dispersion measurements, namely, variance (σ^2) and standard deviation (σ) (Clarke & Cooke, 2004); and 95% confidence interval (CI) (Clarke & Cooke, 2004). Table 5.3 describes how each measurement can be calculated.

Table 5.3: Performance Measurements.

Measurements	Goals	Equation
Mean	Calculate the average of the performance results	$Mean = \frac{1}{c} \sum_{i=1}^c x_i$, where x_i is the performance result of run i , and the $i = 1, 2, \dots, c$ and c is equal to 10
variance (σ^2)	The variance measures how the performance measure results for the 10 runs spread from the mean of these performance measure results	$\sigma^2 = \frac{1}{c} \sum_{i=1}^c (x_i - mean)^2$, where x_i is the performance result of run i , and the $i = 1, 2, \dots, c$ and is c equal to 10
standard deviation (σ)	The standard deviation measures how the performance measure results for the 10 runs spread from the mean of these performance measure results	$\sigma = \sqrt{\sigma^2}$
95% confidence intervals (CI)	produces lower and upper limits for the mean	$95\% \text{ CI} = \text{mean} \pm 1.96 \sqrt{\sigma^2/c}$, where c is equal to 10.

5.6.1 Statistical Analysis of GB

Table 5.4 presents the statistical analysis for all the performance measures of GB when different packet arrival probability values are used. The mean of mql when the packet arrival probability value is 0.18 (in case of no congestion) is 0.446, and σ^2 and σ are 2.66194E-06 and 0.001631545, respectively. These values are extremely small, thereby indicating the absence of a wide dispersion from their computed mean. The 95% CI value at the same packet arrival probability value is 0.001011223. The upper and lower limits are 0.447239686 and 0.445217239, respectively, which suggest accurate mean results. The mean of GB-T result is 0.5 when the packet arrival probability value is 0.93. Then, σ^2 , σ , and 95% CI are extremely small (0), which indicates accurate mean results. That is, no wide dispersion occurs from their computed mean. The DP and PL results when the packet arrival probability values are 0.93 and 0.63, respectively, achieve satisfactory statistical performance measure results and extremely small values. The result of the PL measure of dispersion is 0 when the packet arrival probability value is 0.63. Moreover, the DP measure of dispersion for σ^2 is 1.6558E-05 and σ is 0.004069149 at the same packet arrival probability value.

Table 5.4: GB Statistical Analysis.

	mqj-0.18	mqj-0.33	mqj-0.48	mqj-0.63	mqj-0.78	mqj-0.93
Average =	0.446228463	1.125533331	2.873645598	6.968457996	10.43046332	11.95039861
Variance =	2.66194E-06	8.7454E-05	0.002794472	0.008708819	0.000240007	0.000148968
Standard Deviation =	0.001631545	0.009351684	0.052862765	0.093321055	0.015492158	0.012205229
95% Confidence Interval =	0.001011223	0.005796127	0.032764079	0.057839926	0.009601963	0.007564741
Upper Limit =	0.447239686	1.131329458	2.906409678	7.026297922	10.44006528	11.95796335
Lower Limit =	0.445247239	1.119737203	2.840881519	6.91061807	10.42086136	11.94283387
	T-0.18	T-0.33	T-0.48	T-0.63	T-0.78	T-0.93
Average =	0.177184716	0.319083189	0.441568245	0.495871356	0.499975835	0.5
Variance =	4.07922E-07	1.33068E-06	2.88496E-06	6.61415E-08	1.56513E-10	0
Standard Deviation =	0.000638688	0.001153551	0.001698516	0.00025718	1.25105E-05	0
95% Confidence Interval =	0.000395856	0.000744965	0.001052732	0.000159399	7.75394E-06	0
Upper Limit =	0.177583572	0.319498154	0.442620977	0.496030755	0.499983589	0.5
Lower Limit =	0.176791861	0.318368223	0.440515513	0.495711958	0.499968081	0.5
	D-0.18	D-0.33	D-0.48	D-0.63	D-0.78	D-0.93
Average =	2.518408871	3.527371825	6.507552568	14.05290265	20.8619349	23.90079723
Variance =	7.87275E-05	0.000520771	0.010243991	0.033939152	0.000961332	0.000595871
Standard Deviation =	0.008872854	0.022820418	0.10119602	0.184225818	0.031005352	0.024410459
95% Confidence Interval =	0.005499351	0.014143982	0.062731068	0.1140182247	0.019216963	0.015129481
Upper Limit =	2.523908222	3.541515807	6.570283436	14.1670840	20.88115186	23.91592671
Lower Limit =	2.51290952	3.513227844	6.444821301	13.93872041	20.84271794	23.88566774
	DP-0.18	DP-0.33	DP-0.48	DP-0.63	DP-0.78	DP-0.93
Average =	0	0.025572887	0.077092686	0.2122825394	0.358544955	0.462304556
Variance =	0	0.025566201	3.05558E-06	1.6558E-05	8.18907E-07	2.42315E-07

Standard Deviation =	0	0.025576674	0.001748022	0.004069149	0.000904935	0.000492255
95% Confidence Interval =	0	0.02551711	0.001083415	0.002522038	0.000560874	0.000305097
Upper Limit =	0	0.025559483	0.078176101	0.214804577	0.35910583	0.462606653
Lower Limit =	0	0.025571599	0.076009271	0.2097605	0.357984081	0.461996459
	PL-0.18	PL-0.33	PL-0.48	PL-0.63	PL-0.78	PL-0.93
Average =	0	0	0	0	0	7.44614E-08
Variance =	0	0	0	0	0	4.99005E-14
Standard Deviation =	0	0	0	0	0	2.23384E-07
95% Confidence Interval =	0	0	0	0	0	1.38452E-07
Upper Limit =	0	0	0	0	0	2.12914E-07
Lower Limit =	0	0	0	0	0	-6.3991E-08

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5.6.2 Statistical Analysis of GB-MMBP-2

Table 5.5 presents the statistical analysis of GB-MMBP-2 for all the performance measures when different values of packet arrival probability are used. The mean of mql is 1.7 when the packet arrival probability value is 0.18 (without congestion), and σ^2 and σ are 0.004990612 and 0.070644263, respectively. These values are extremely small, which indicates the absence of a wide dispersion from their computed mean. The 95% CI value at the same packet arrival probability value is 0.043784963. The upper and lower limits are 1.745648621 and 1.658078694, respectively, which suggest accurate mean results. The mean of the T result of GB-MMBP-2 is 0.499950626 when the packet arrival probability value is 0.93, and the resulting variance σ^2 , standard deviation σ , and 95% CI are extremely small, i.e., 2.92567E-09, 5.40895E-05, and 3.35244E-05, respectively, which indicate accurate mean results. That is, no wide dispersion is observed from their computed mean. Moreover, the upper and lower limits are 0.499984151 and 0.499917102, respectively.

The PL statistical result is 2.44636E-05 when the packet arrival probability value is 0.48. In addition, the DP result is 0.119539809 when the packet arrival probability value is 0.63. Both results provide satisfactory statistical performance measures and extremely small values. The result of the PL measure of dispersion is $\sigma^2 = 1.48254E-10$ and $\sigma = 1.21759E-05$. Moreover, the upper and lower limits for PL under the same packet arrival probability value are 0.499984151 and 0.499917102, respectively; these values are good indicators of the validity of the results. The DP measure of dispersion for GB-MMBP-2 presents small results. Meanwhile, the variance σ^2 is 6.62227E-05 and standard deviation σ is 0.008137731. The 95% CI, the upper limit, and the lower limit are 0.005043725,

0.124583534, and 0.114496084, respectively, which also suggest that the results are correct.



Table 5.5: GB-MMBP-2 Statistical Analysis.

	mql-0.18	mql-0.33	mql-0.48	mql-0.63	mql-0.78	mql-0.93	
Average =	1.701863658	2.904358911	6.076772039	9.942172223	11.40539548	11.99185458	mql-GB-MMBP-2
Variance =	0.004990612	0.045772137	0.041987162	0.017436616	0.004528748	0.000939016	
Standard Deviation =	0.070644263	0.213944238	0.204907691	0.132047778	0.067295973	0.030643373	
95% Confidence Interval =	0.043784963	0.132601576	0.127000769	0.081842557	0.04170971	0.01899261	
Upper Limit =	1.745648621	3.036960487	6.203772808	10.02401478	11.44710519	12.01084719	
Lower Limit =	1.658078694	2.771757335	5.94977127	9.860329667	11.36368577	11.97286197	
	T-0.18	T-0.33	T-0.48	T-0.63	T-0.78	T-0.93	
Average =	0.368858967	0.413698673	0.473779268	0.497537895	0.499679107	0.499950626	T-GB-MMBP-2
Variance =	1.05639E-06	1.53066E-05	5.99438E-06	2.52836E-07	3.44002E-08	2.92567E-09	
Standard Deviation =	0.003250211	0.003647815	0.00248342	0.000502828	0.000185473	5.40895E-05	
95% Confidence Interval =	0.002014465	0.00260897	0.00151747	0.00031165	0.000114955	3.35244E-05	
Upper Limit =	0.340873432	0.41594957	0.47296738	0.497849546	0.499794062	0.499984151	
Lower Limit =	0.336844502	0.411437776	0.474261797	0.497226245	0.499564152	0.499917102	
	D-0.18	D-0.33	D-0.48	D-0.63	D-0.78	D-0.93	
Average =	5.021156011	7.017057422	12.7710266	19.98265347	22.82541054	23.98607175	D-GB-MMBP-2
Variance =	0.02923486	0.215376891	0.150675341	0.065498154	0.016722068	0.003463417	
Standard Deviation =	0.170982046	0.464087158	0.388169218	0.25592607	0.129313836	0.058850803	
95% Confidence Interval =	0.105973822	0.287638915	0.240585353	0.1586217073	0.080148073	0.036475436	
Upper Limit =	5.127129834	7.304696337	13.01161195	20.14125488	22.90555861	24.02254748	

Lower Limit =	4.915182189	6.729418506	12.53044125	19.82401146	22.74526247	23.94959631
	DP-0.18	DP-0.33	DP-0.48	DP-0.63	DP-0.78	DP-0.93
Average =	3.52358E-06	0.000101112	0.027019217	0.119539809	0.21840077	0.300840661
Variance =	5.17609E-11	0.000108617	1.46293E-05	6.62227E-05	8.93611E-06	7.57696E-06
Standard Deviation =	7.1945E-06	0.00011737	0.003824825	0.008137731	0.002989333	0.002752628
95% Confidence Interval =	0	0.00012709	0.002370607	0.005043725	0.001852774	0.001706065
Upper Limit =	3.52358E-06	0.000136309	0.029389824	0.124583534	0.220253544	0.302546726
Lower Limit =	3.52358E-06	0.00012111	0.02464861	0.114496084	0.216547996	0.299134596
	PL-0.18	PL-0.33	PL-0.48	PL-0.63	PL-0.78	PL-0.93
Average =	0	6.81459E-05	2.44636E-05	5.6553E-05	0.00010555	0.000185548
Variance =	0	7.49604E-05	1.54767E-10	1.48254E-10	3.95841E-10	4.35468E-10
Standard Deviation =	0	8.24665E-06	1.24406E-05	1.21759E-05	1.98957E-05	2.08679E-05
95% Confidence Interval =	0	9.97021E-05	7.7106E-06	7.54659E-06	1.23313E-05	1.29338E-05
Upper Limit =	0	9.36795E-05	3.21742E-05	6.40996E-05	0.000117881	0.000198482
Lower Limit =	0	7.91654E-05	1.6753E-05	4.90064E-05	9.32184E-05	0.000172614

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5.6.3 Statistical Analysis of GBFL

Table 5.6 presents the GBFL statistical analysis for all the performance measures when different values of packet arrival probability are used. The mean of mql is 0.445 when the packet arrival probability value is 0.18 (in case of no congestion), and σ^2 and σ values are 2.50981E-06 and 0.001584238, respectively. These values are extremely small, which indicates the absence of a wide dispersion from their computed mean. The 95% CI at the same packet arrival probability value is 0.000981903. The upper and lower limits are 0.446369907 and 0.444406101, respectively, which suggest accurate mean results. The mean of the GBFL T result is 0.49 when the packet arrival probability value is 0.93, and the values of σ^2 , σ , and 95% CI are extremely small, i.e., 1.13175E-12, 1.06384E-06, and 6.59361E-07, respectively, which indicate accurate mean results. That is, no wide dispersion is observed from their computed mean. Moreover, the upper and lower limits are 0.499999963 and 0.499998644, respectively. The PL statistical result is 2.90421E-05 when the packet arrival probability value is 0.48. In addition, the DP result is 0.291115018 when the packet arrival probability value is 0.63. Both results provide satisfactory statistical performance measures and extremely small values. The results of the PL measure of dispersion are $\sigma^2 = 1.42847E-09$ and $\sigma = 3.77951E-05$. Moreover, the upper and lower limits for PL under the same packet arrival probability value are 5.24673E-05 and 5.61688E-06, respectively. These values are good indicators of the validity of the results. The results of the DP measure of dispersion are $\sigma^2 = 0.02880898$ and $\sigma = 0.169732082$. The 95% CI, the upper limit, and the lower limit are 0.105199101, 0.396314119, and 0.185915917, respectively, which also suggest that the results are correct.

Table 5.6: GBFL Statistical Analysis.

	mql-0.18	mql-0.33	mql-0.48	mql-0.63	mql-0.78	mql-0.93
Average =	0.445388004	1.219566413	5.042375737	11.91109603	12.49995457	12.4999799
Variance =	2.50981E-06	0.000225694	0.024435884	0.000628831	4.91505E-10	1.10549E-10
Standard Deviation =	0.001584238	0.015023127	0.156319813	0.025076505	2.21699E-05	1.05142E-05
95% Confidence Interval =	0.000981703	0.00931126	0.096886244	0.015542293	1.37408E-05	6.51666E-06
Upper Limit =	0.446869907	1.228877672	5.13926198	11.92663833	12.49996831	12.49998641
Lower Limit =	0.444406101	1.210255153	4.945489493	11.89555374	12.49994083	12.49997338
	D-0.18	D-0.33	D-0.48	D-0.63	D-0.78	D-0.93
Average =	0.185977625	0.327093269	0.46426197	0.499874735	0.499999458	0.499999304
Variance =	3.66522E-07	1.34911E-06	2.90064E-06	5.5737E-10	1.20361E-12	1.13175E-12
Standard Deviation =	0.000605411	0.00116151	0.001703127	2.36087E-05	1.09709E-06	1.06384E-06
95% Confidence Interval =	0.000375291	0.000719898	0.001055589	1.46325E-05	6.79971E-07	6.59361E-07
Upper Limit =	0.186352855	0.327813168	0.46531756	0.499889367	0.500000138	0.499999963
Lower Limit =	0.185602394	0.326379371	0.463206381	0.499860102	0.499998778	0.499998644
	D-0.18	D-0.33	D-0.48	D-0.63	D-0.78	D-0.93
Average =	2.445785307	3.738200507	10.86066692	23.82816748	24.99993622	24.99999461
Variance =	7.76975E-05	0.001567433	0.088929973	0.002502469	3.16938E-09	1.43004E-09
Standard Deviation =	0.008814617	0.039590815	0.2982129	0.050024682	5.62973E-05	3.78158E-05
95% Confidence Interval =	0.005463256	0.024538191	0.184829876	0.03100505	3.48928E-05	2.34381E-05
Upper Limit =	2.451248563	3.762738698	11.04549679	23.85916653	24.99997112	25.00001805
Lower Limit =	2.440322051	3.713662316	10.67583704	23.79715643	24.99990153	24.99997117
	DP-0.18	DP-0.33	DP-0.48	DP-0.63	DP-0.78	DP-0.93

Average =	0.030270426	0.057551543	0.111313923	0.291115018	0.427585331	0.548473772
Variance =	0.000251071	0.06131075	0.023787811	0.02880898	0.018837481	0.017404922
Standard Deviation =	0.015845232	0.065426662	0.154232975	0.169732082	0.137249704	0.131927716
95% Confidence Interval =	0	0.069947941	0.095592832	0.105199101	0.085066685	0.081768143
Upper Limit =	0.030270426	0.074980784	0.206906755	0.396314119	0.512652016	0.630241915
Lower Limit =	0.030270426	0.079076627	0.015721092	0.185915917	0.342518646	0.466705629
Average =	0	0	PL-0.48	PL-0.63	PL-0.78	PL-0.93
Variance =	0	0	2.90421E-05	0	0	0
Standard Deviation =	0	0	1.42847E-09	0	0	0
95% Confidence Interval =	0	0	3.77951E-05	0	0	0
Upper Limit =	0	0	2.34252E-05	0	0	0
Lower Limit =	0	0	5.24673E-05	0	0	0
			5.61688E-06	0	0	0

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5.7 Chapter Summary

This chapter presents the performance evaluation for the proposed methods (i.e., GB, GB–MMBP-2, and GBFL) compared with existing methods in terms of mql, T, D, PL, and DP. The proposed methods achieve the objectives of reducing the number of parameters and enhancing the performance measure results. The results of the proposed GB method are compared with those of the DGRED, BLUE, ERED, and adaptive max threshold methods. The performance measure results of mql, D, and PL for GB are the best when light or heavy congestion occurs. In addition, the DP results for GB are higher than those of the other compared methods because GB starts dropping packets earlier than the other methods. All the compared methods provide almost similar T results. Moreover, the validation process is necessary to provide evidence that simulation results are correct and simulation is working correctly. Therefore, a discrete-time analytical model is used for the GB method. The results obtained by the analytical model are compared with the results obtained by the simulation to validate and prove that the simulation results are correct, and thus, the simulation is working correctly. The obtained results show that GB simulation and the GB analytical model provide similar performance measure results.

Moreover, the results of the proposed GB–MMBP-2 method are compared with those of GB–BP, BLUE–MMBP-2, and BLUE–BP. The performance results of the proposed GB–MMBP-2 present lower mql and D than those of the other methods because the numbers of queued packets are smaller in GB–MMBP-2 even during heavy congestion. In addition, all the compared methods exhibit similar T results when the packet arrival probability value is above 0.33. In case of heavy congestion, GB–MMBP-2 and BLUE–MMBP-2 drop the lowest numbers of packets compared with the other methods.

The results of the proposed GBFL are compared with those of GB, GREDFL, and REDD1. The results indicate that the GB and GBFL methods provide the best mql, D, and PL in light and heavy congestion cases. Furthermore, all the compared methods exhibit similar T results. Meanwhile, GB and GBFL achieve the best and worst PL results, respectively, when light congestion and heavy congestion occur.

