

## CHAPTER THREE

### RESEARCH METHODOLOGY

#### 3.1 Background

Router buffers should be managed to maintain network performance and avoid congestion because routers handle packet switching among different networks. Subsequently, a suitable congestion control method, such as AQM methods, should be applied to manage router buffers.

In this chapter, two congestion control methods have been proposed, namely, GB and GBFL, to detect congestion at an early stage before the buffer overflows and to overcome the limitations of existing methods. Generally, the proposed methods aim to overcome the limitations of earlier methods, particularly the BLUE method. These limitations include sensitivity to parameter initialization, slow adjustment, and inability to stabilize  $q_l$  in all scenarios. In addition a discrete time performance evaluation is proposed to evaluate the proposed GB method under bursty and correlated traffic using two states MMBP, instead of BP that fails to represent the aggregated traffics which is bursty and correlated at natural.

This chapter is organized as follows: Research methodology phases discussed in Sections 3.2. Section 3.3 presents the proposed GB method. Section 3.4 explains the evaluating for the proposed method using MMBP-2. Section 3.5 presents the discrete-time analytical model for the GB method. Section 3.6 discusses the design considerations of the other proposed method namely, GBFL. Section 3.7 explains the performance measures used to evaluate the proposed method. Finally, Section 3.6

provides the summary and the conclusions.

### 3.2 Research Methodology

This section briefly discusses the research methodology, which is based on a set of sequential processes. These processes are organized into five phases, as illustrated in Figure 3.1. Each process has its own goal.

#### 3.2.1 Phase One: Literature Review

A survey of existing congestion control methods according to their various types, such as Transport Control Protocol (TCP) and AQM, is conducted in this phase. The methods are reviewed based on their techniques, performance advantages, disadvantages, utilized congestion measures (e.g., aq, instantaneous ql, and price), the manner DP is calculated, and the type of packet dropping policies (i.e., randomly, and periodically). The outcome of this phase is a report on the literature survey.

#### 3.2.2 Phase Two: Literature Analysis

The gap in AQM methods is identified based on the survey conducted in the previous phase. Subsequently, the problem statement is determined in this phase.

#### 3.2.3 Phase Three: Design the of Proposed Method

The BLUE method is set as one of the potential AQM methods that could fill in the gap in the literature. This method is analyzed carefully from a technical prospective. Then, the drawbacks of the proposed method are addressed, and its strengths are maximized to obtain a new AQM method.

The proposed method is implemented and evaluated according to well-known measures, namely, mean queue length (mq), delay (D), throughput (T), PL, and DP.

### 3.2.4 Phase Four: Evaluating and validating Models Using Discrete-time Queue

A discrete-time performance analysis of the proposed method is conducted in the previous phase. In the current phase, we establish a new model for performance analysis under bursty and correlated traffic that uses MMBP as the traffic source (also called the MMBP-2 model). The outcomes of the proposed model are compared with those of the proposed method that uses Bernoulli process (BP) to model traffic sources. The effectiveness of the evaluation model is also highlighted.

Finally, a discrete-time analytical model is presented. The results of the proposed model are compared with the simulation results from the previous phase and the results of the analytical model for validation.

### 3.2.5 Phase Five: Fuzzy-based AQM

A new method for congestion control based on the fuzzy inference process (FIP) is proposed at this phase to reduce the parameterization problem of the proposed method in phase three. The fuzzy-based method is designed, implemented, and evaluated in this phase on the basis of  $mql$ ,  $D$ ,  $T$ ,  $PL$ , and  $DP$ .

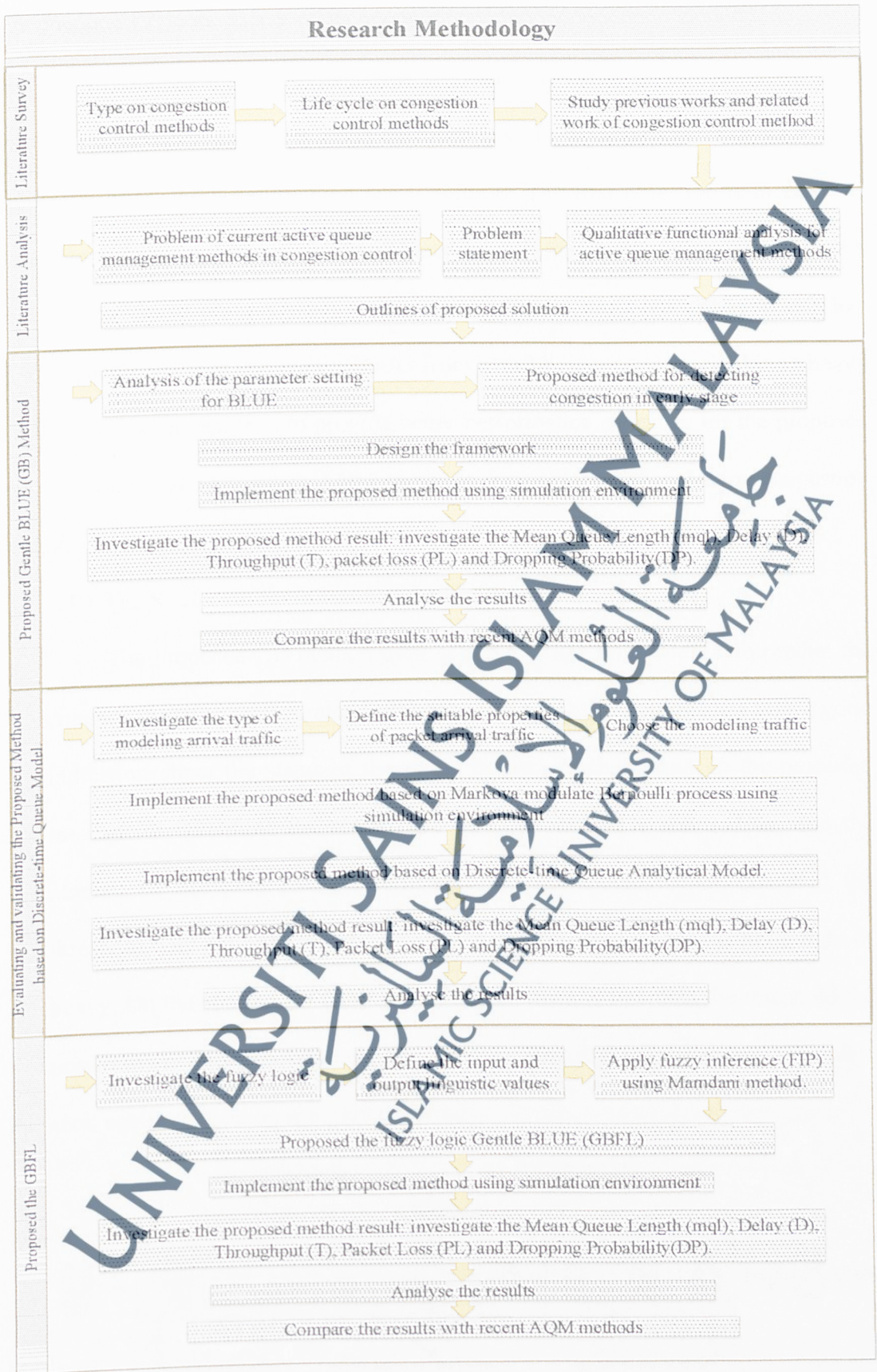


Figure 3.1: Research Methodology

### 3.3 Proposed Gentle BLUE (GB) Method

The proposed method extends the well-known BLUE to provide a dynamic mechanism for calculating DP based on the status of the router buffer  $ql$ . The main objectives of the proposed method are as follows. The first objective is to ease the parameter setting problem in the BLUE method. Ultimately, having zero parameters in the management process becomes impossible. The second objective is to stabilize  $ql$  at a specific value to prevent the buffer from overflowing, particularly during heavy traffic. The last objective is to provide better performance measures for the proposed method compared with other AQM methods, particularly when heavy congestion occurs.

#### 3.3.1 The Router Buffer in Gentle BLUE (GB):

The proposed GB method used  $ql$  and a single threshold  $Th$  to predict the congestion status as illustrated in Figure 3.2. The  $Th$  and  $ql$  together give a good indication about the status of the router buffer, which is used, in the proposed method, to determine the status of congestion and as a result determine the number of dropping packet. Particularly, if the queue length exceeded the threshold, this indicates that the possibility of congestion is high either a light or heavy. On the contrary, if the queue length is low and less than the threshold the possibility of congestion is very low. Furthermore, if  $ql$  is greater than the buffer size, heavy congestion is highly occurred.

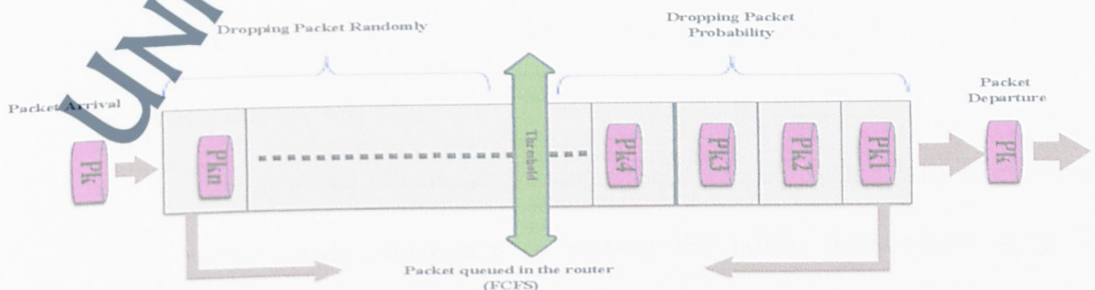


Figure 3.2 : Router Buffer for the Gentle BLUE (GB) Method

### 3.3.2 Updates The Dropping Probability For Gentle BLUE Method:

BLUE computes  $ql$  and compare it with the threshold. When  $ql$  at the router buffer surpasses the threshold, BLUE increases DP with a fixed value  $P_{in}$  (DP increment) by using the following equation  $DP=DP+P_{in}$ , to manage the congestion and maintain  $ql$  at a reasonable value while avoiding buffer overflow. When buffer length is empty or the link is idle, DP is decreased according the following equation  $DP=DP- P_{de}$ . The fixed value that is used by BLUE reduces the performance when the network flow changed magnificently.

The proposed GB method updates the DP value dynamically to stabilize  $ql$  at a specific value/range and to prevent the buffer from overflowing. This dynamic-based method overcomes the slow-to-congestion response shortage in existing methods and provides better management for the router buffer. Unlike the original BLUE method, which has a slow response when sudden heavy congestion occurs because it uses fixed parameter ( $P_{in}$  and  $P_{de}$ ) values to adjust DP, the proposed method predicts congestion before it occurs and responds by using dynamically updated values. The dropping value is dynamically calculated based on  $ql$  and the remaining buffer capacity, which improves network performance. The proposed GB uses the values of threshold ( $Th$ ) and  $ql$  in congestion status (i.e., no congestion, light congestion, and heavy congestion) prediction. Together,  $Th$  and  $ql$  provide a good indication of the status of the router buffer to determine the number of dropped packets. Figure 3.3 illustrates how to calculate GB-DP.

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dynamic-based method overcomes the slow-to-congestion response shortage in existing methods and provides better management for the router buffer.

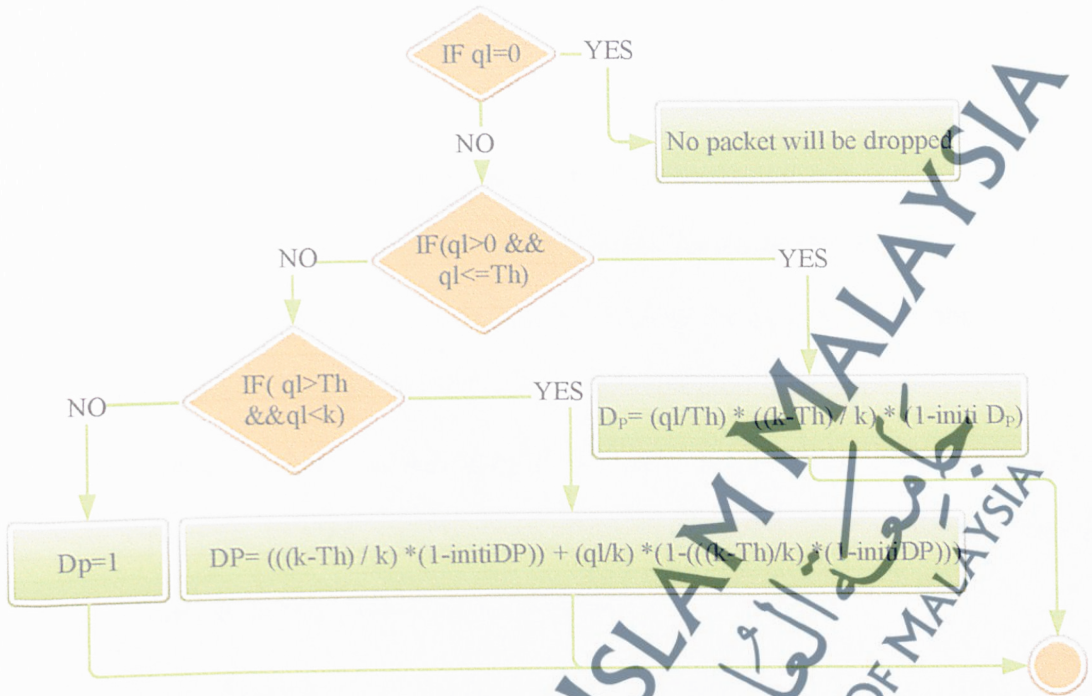


Figure 3.3: The Flowchart of Updating (GB-DP) Value

The proposed GB method adaptively adjusts the DP value to prevent buffer overflow as follows:

1. If the router buffer is empty, and  $ql$  is equal to 0, then no packet will be dropped.
2. If  $ql$  is greater than zero and less than or equal to the  $Th$  value, then no congestion is present. In such case, DP is calculated as shown in Equation 3.1.

$$DP = \left( \left( \frac{ql}{Th} \right) * \left( \frac{k-Th}{k} \right) * (1 - initiDP) \right) \dots \dots \dots (3.1)$$

As indicated in Equation 3.1, the DP value is proportional to the ratio between  $ql$  and the  $Th$  value. Consequently, when  $ql$  value is low, the DP value is set as small to prevent dropping more packets when congestion is absent.

Moreover, DP is linked to the buffer remaining capacity above  $Th$ . Hence, if the remaining capacity is slightly smaller than the total buffer size, then the DP value is increased to prevent the queue from reaching the  $Th$  point. Finally, the calculated DP is inversely proportional to the  $initiDP$  ( $1 - initiDP$ ). Therefore, if the  $initiDP$  is high, then congestion is being firmly controlled. The calculated DP value can ease this firmness and vice versa. In summary, Equation 3.1 is used when light congestion or no congestion occurs. In general, when the  $ql$  value is less than the  $Th$  value, the DP value is set as low.

3. If the  $ql$  value is greater than the  $Th$  value and  $ql$  is less than the capacity of the router buffer, then light and heavy congestion may be present. The GB method uses Equation 3.2 to calculate DP.

$$DP = \left( \left( \frac{K-Th}{K} \right) * (1 - initiDP) + \left( \frac{ql}{k} \right) * \left( 1 - \left( \left( \frac{K-Th}{K} \right) * (1 - initiDP) \right) \right) \right) \dots \quad (3.2)$$

where  $K$  is the total buffer size. Subsequently, the fraction  $\left( \frac{K-Th}{K} \right)$  represents the ratio of the remaining capacity after  $Th$  with respect to the total capacity of the buffer. Lastly,  $initiDP$  is the initial value of DP.

As indicated in Equation 3.2, the DP value is proportional to the buffer remaining capacity above  $Th$  and  $ql$ . Unlike in the previous case, Equation 3.2 is inversely proportional to the remaining capacity above  $Th$ . In this case, congestion is already present and increasing the DP value inversely. The remaining capacity is necessary to prevent the router buffer from overflowing. Hence, GB manages congestion at an early stage before  $ql$  reaches buffer capacity and the buffer overflows.

Finally, if the  $ql$  value is the same as the capacity of the router buffer, then the DP value is set as 1, which indicates that every arriving packet will be dropped.

### 3.4 Evaluating the Proposed Method Under Bursty and Correlated Traffic Using Markov Modulate Bernoulli Process:

Internet traffic is naturally aggregated, and thus, modeling this type of traffic requires an approach that captures the discretized, bursty, and correlation characteristics of traffic. Accordingly, MMBP is a suitable candidate that can represent all the aforementioned characteristics. By contrast, renewal traffic (BP and PP), MMPP and MMFF are unable to capture these characteristics, particularly correlated traffic and bursty traffic.

In this section, a discrete-time performance analysis approach is presented for the GB method under bursty traffic and correlated traffic by using MMBP-2 as the traffic source.

MMBP-2 uses two states, and each state has a different packet arrival probability value (i.e.,  $\alpha_0$  and  $\alpha_1$ ) as illustrated in Figure 3.4. Thus, MMBP-2 first defines the state of arrival, i.e., state 1 or state 2. Then, the occurrence of packet arrival is checked based on the probability for this state. A decision on whether a packet arrives should be made based on the packet arrival probability of the states. The initial state in GB-MMBP-2 is state 1. As previously mentioned, the next arriving packet can either remain in the same state or transfer to the next state. We place a high priority for the next packet to remain in the same state with a probability of 0.9, whereas the transfer probability is 0.1. The transfer probability value results from  $p(s_1) + p(s_2) = 1$ , where  $p(s_1)$  and  $p(s_2)$  represent the probability that the packet arrives at state 1 and state 2, respectively. Each

state has a different packet arrival probability, which is  $\alpha_0$  for state 1 and  $\alpha_1$  for state 2. Figure 3.5 illustrates the definition of packet arrival states.

After the state of packet arrival probability is defined, a random number is generated according to linear congruential generators. If the random number is less than the packet arrival probability for the defined state, then packet arrival is increased; otherwise, no packet has arrived.

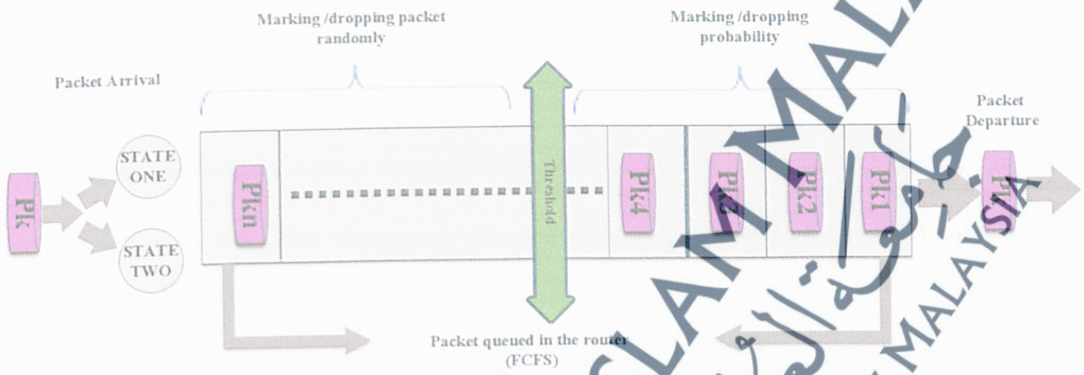


Figure 3.4: Single Router Buffer for GB-MMBP-2.

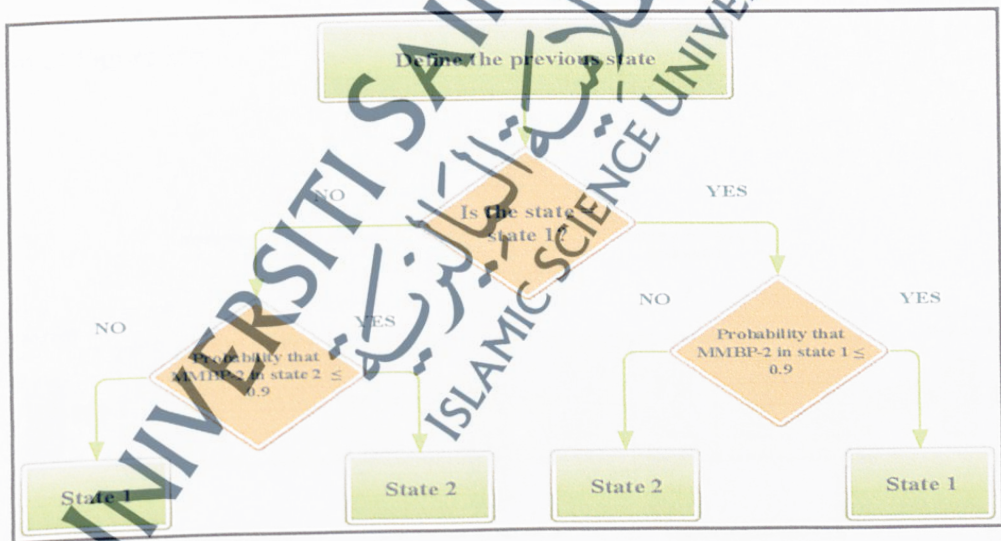


Figure 3.5: Defining the State of Packet Arrival.

### 3.5 Discrete-time Queue Analytical Model for the GB Method

This section presents the discrete-time analytical model for the GB method. The obtained performance measure results of the GB analytical model are compared with the obtained results of GB simulation to validate and prove that the performance measure results of the latter are correct. The comparison is based on the following performance measures:  $mql$ ,  $D$ ,  $T$ ,  $PL$ , and  $DP$ .

One of the popular approaches used to model and evaluates the performance measures of computer networks and communications is discrete-time queue. The discrete-time approach uses a single time slot, and multiple events may occur in each slot. Packet arrival and/or departure can occur, as discussed in Chapter Two, Section 2.8.

In this section, a discrete-time analytical model for the GB method is applied. A finite discrete-time queuing system model capacity ( $k$  packets) is used. In addition, BP is adopted as the arrival process. Furthermore, a single  $M$  is used in this model, as shown at Figure 3.6.



Figure 3.6: Router Buffer of the GB Analytical Model

### 3.5.1 Calculation of Packet Arrival Probability

As previously mentioned, the GB method dynamically updates DP based on  $q_l$  and  $Th$  as follows:

$$DP \begin{cases} \text{if } q_l = 0 & , DP = 0 \\ \text{if } 0 < q_l \leq Th & , DP = \left( \left( \frac{q_l}{Th} \right) * \left( \frac{K - Th}{k} \right) * (1 - \text{initiDP}) \right) \\ \text{if } Th < q_l < K - 1 & , DP = \left( \left( \frac{K - Th}{K} \right) * (1 - \text{initiDP}) + \left( \frac{q_l}{k} \right) * \left( 1 - \left( \left( \frac{K - Th}{K} \right) * (1 - \text{initiDP}) \right) \right) \right) \\ \text{if } q_l = K & , DP = 1 \end{cases}$$

- If  $q_l = 0$ , then  $DP = 0$  indicates that no packet will be dropped.
- If  $q_l$  is greater than zero and less than or equal to  $Th$  in the router buffer, then congestion occurs. This condition decreases the probability of packet arrival ( $\alpha_q$ ) with DP values. Moreover, packet dropping will increase from 0, and its value can be calculated using GB Equation 3.1, as discussed in detail in Section 3.3. This equation is based on the queue status, i.e., DP increases as long as queue increases.
- If  $q_l$  is greater than  $Th$  and less than the capacity ( $K$ ), then  $\alpha_q$  decreases with the DP value. DP is increased dynamically according to GB Equation 3.2, as discussed in detail in Section 3.3.
- Finally, if  $q_l$  is equal to  $K$ , then  $\alpha_q$  is equal to 0 given that DP is equal to 1. The values of  $\alpha_q$  are as follows:

$$\alpha \begin{cases} \text{if } q_l = 0 & , \alpha_{q_l} = \alpha \\ \text{if } 0 < q_l \leq Th & , \alpha_{q_l} = \alpha - \alpha * \left( \left( \frac{q_l}{Th} \right) * \left( \frac{K - Th}{k} \right) * (1 - \text{initiDP}) \right) \\ \text{if } Th < q_l < K & , \alpha_{q_l} = \alpha - \alpha * \left( \left( \frac{K - Th}{K} \right) * (1 - \text{initiDP}) + \left( \frac{q_l}{k} \right) * \left( 1 - \left( \left( \frac{K - Th}{K} \right) * (1 - \text{initiDP}) \right) \right) \right) \\ \text{if } q_l = K & , \alpha_{q_l} = 0 \text{ or } \alpha_{q_l} = \alpha - 1 * \alpha \end{cases}$$

### 3.5.2 State Chart Diagram

The following assumption is used to create the state chart diagram.  $\alpha_{ql}$  denotes the packet arrival probability value in a slot. Furthermore, assume that  $\beta$  is the probability of packet departure from a slot. Assume also that the queuing system model is in equilibrium, and the ql process is a Markov chain with finite state spaces, which are  $\{0, 1, 2, 3, \dots, th-1, th, th+1, \dots, K-1, K\}$ . Figure 3.7 shows the state chart diagram for the GB discrete-time analytical model.

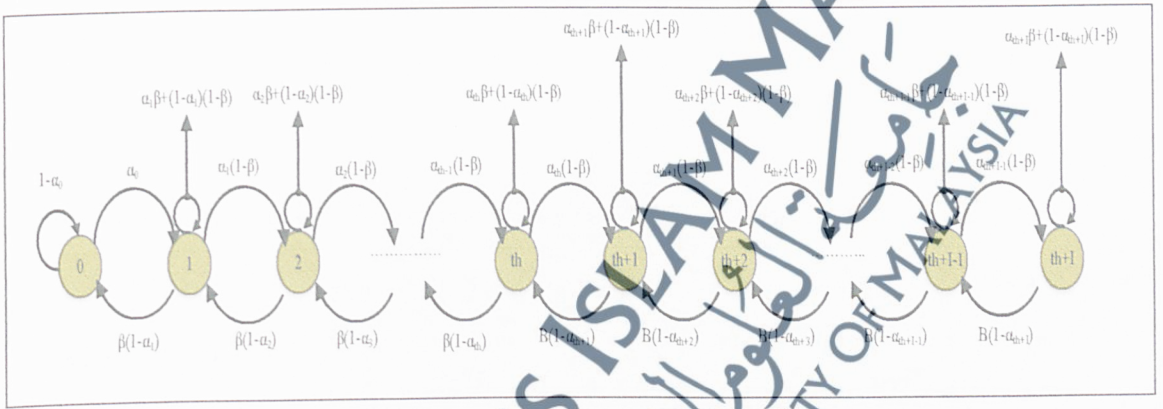


Figure 3.7: State Chart Diagram.

The balance equations represented as Equations 3.3 to 3.10 for the GB analytical model that are derived from the state chart diagram are as follows:

$$p_0 = (1 - \alpha_0)p_0 + [\beta(1 - \alpha_1)]p_1 \dots \dots \dots (3.3)$$

$$p_1 = \alpha_0 p_0 + [\alpha_1 \beta + (1 - \alpha_1)(1 - \beta)]p_1 + [\beta(1 - \alpha_2)]p_2 \dots \dots \dots (3.4)$$

$$p_2 = [\alpha_1(1 - \beta)]p_1 + [\alpha_2 \beta + (1 - \alpha_2)(1 - \beta)]p_2 + [\beta(1 - \alpha_3)]p_3 \dots \dots \dots (3.5)$$

.. .. .  
 .. .. .  
 .. .. .

$$p_{Th-1} = [\alpha_{Th-2}(1 - \beta)]p_{Th-2} + [\alpha_{Th-1} \beta + (1 - \alpha_{Th-1})(1 - \beta)]p_{Th-1} + [\beta(1 - \alpha_{Th})]p_{Th} \dots \dots \dots (3.6)$$

$$p_{Th} = [\alpha_{Th-1}(1 - \beta)]p_{Th-1} + [\alpha_{Th} \beta + (1 - \alpha_{Th})(1 - \beta)]p_{Th} + [\beta(1 - \alpha_{Th+1})]p_{Th+1} \dots (3.7)$$

$$p_{Th+1} = [\alpha_{Th}(1 - \beta)]p_{Th} + [\alpha_{Th+1} \beta + (1 - \alpha_{Th+1})(1 - \beta)]p_{Th+1} + [\beta(1 - \alpha_{Th+2})]p_{Th+2} \dots (3.8)$$

.. .. .  
 .. .. .  
 .. .. .

$$p_{Th+l-1} = [\alpha_{Th+l-2}(1 - \beta)]p_{Th+l-2} + [\alpha_{Th+l-1} \beta + (1 - \alpha_{Th+l-1})(1 - \beta)]p_{Th+l-1} + [\beta(1 - \alpha_{Th+l})]p_{Th+l} \dots (3.9)$$

$$p_{Th+l} = [\alpha_{Th+l-1}(1 - \beta)]p_{Th+l-1} + [\alpha_{Th+l} \beta + (1 - \alpha_{Th+l})(1 - \beta)]p_{Th+l} \dots (3.10)$$

Where,  $k = Th + l$

The equilibrium probabilities in the GB analytical model are obtained as follow:

$$P1 = \frac{\alpha_0}{\beta(1-\alpha_1)} P_0 \dots (3.11)$$

$$P2 = \frac{\alpha_0 \alpha_1 (1-\beta) P_0}{\beta^2 (1-\alpha_1)(1-\alpha_2)} \dots (3.12)$$

$$P3 = \frac{\alpha_0 \alpha_1 \alpha_2 (1-\beta)^2 P_0}{\beta^3 (1-\alpha_1)(1-\alpha_2)(1-\alpha_3)} \dots (3.13)$$

$$P_{Th+l} = \frac{\alpha_0 \alpha_1 \dots \alpha_{Th+l-1} (1-\beta)^{Th+l-1} p_0}{\beta^{Th+l} (1-\alpha_1)(1-\alpha_2) \dots (1-\alpha_{Th+l})} \dots (3.14)$$

In general,

$$P_{ql} = \frac{\alpha_0 \alpha_1 \dots \alpha_{ql-1} (1-\beta)^{ql-1} p_0}{\beta^{ql} (1-\alpha_1)(1-\alpha_2) \dots (1-\alpha_{ql})} \dots (3.15)$$

where,  $ql$  is the queue state and  $1 \leq ql \leq Th+l$ , and  $k = Th+l$

The probability of no packet (system idle) P0 can be calculated by using the normalizing equation and by applying the steady state to the normalizing equation, as follows:

$$\sum_{q=0}^{k-1} p_{ql} = 1 \equiv \sum_{q=0}^{k-1} p_{ql} \equiv p_0 + p_1 + p_2 + \dots + p_k = 1$$

$$P_0 + \frac{\alpha_0}{\beta(1-\alpha_1)} P_0 + \frac{\alpha_0 \alpha_1 (1-\beta) P_0}{\beta^2 (1-\alpha_1)(1-\alpha_2)} + \frac{\alpha_0 \alpha_1 \alpha_2 (1-\beta)^2 P_0}{\beta^3 (1-\alpha_1)(1-\alpha_2)(1-\alpha_3)} + \dots + \frac{\alpha_0 \alpha_1 \dots \alpha_{Th+1-1} (1-\beta)^{Th+1-1} P_0}{\beta^{Th+1} (1-\alpha_1)(1-\alpha_2) \dots (1-\alpha_{Th+1})} = 1$$

$$P_0 = \left[ 1 + \frac{\alpha_0}{\beta(1-\alpha_1)} + \frac{\alpha_0 \alpha_1 (1-\beta)}{\beta^2 (1-\alpha_1)(1-\alpha_2)} + \frac{\alpha_0 \alpha_1 \alpha_2 (1-\beta)^2}{\beta^3 (1-\alpha_1)(1-\alpha_2)(1-\alpha_3)} + \dots + \frac{\alpha_0 \alpha_1 \dots \alpha_{Th+1-1} (1-\beta)^{Th+1-1}}{\beta^{Th+1} (1-\alpha_1)(1-\alpha_2) \dots (1-\alpha_{Th+1})} \right]^{-1} \dots \dots \dots (3.16)$$

Then, mql can be calculated using the following Equation

$$mql = \sum_{q=0}^{k-1} ql p_{ql} \dots \dots \dots (3.17)$$

After mql is calculated, throughput (T) can be calculated as follows:

$$T = (1 - P_0)\beta = \beta \sum_{q=1}^K P_{ql} \dots \dots \dots (3.18)$$

The D results are calculated based on mql and T, using Little's law as follows:

$$D = \frac{mql}{T} \dots \dots \dots (3.19)$$

PL is calculated according to the following Equation:

$$PL = (1 - \beta) P_K \dots \dots \dots (3.20)$$

Finally, DP are computed according to Equations 3.1 and 3.2 as follows:

$$DP = \sum_{ql=1}^{Th} \left( \left( \frac{ql}{th} \right) * \left( \frac{K-Th}{k} \right) * (1 - initiDP) \right) * P_{ql} + \sum_{ql=th+1}^{k-1} \left( \left( \frac{K-Th}{K} \right) * (1 - initiDP) + \left( \frac{ql}{k} \right) * \left( 1 - \left( \left( \frac{K-Th}{K} \right) * (1 - initiDP) \right) \right) \right) * P_{ql} \dots \dots (3.21)$$

### 3.6 The Proposed Gentle BLUE Fuzzy Logic Method (GBFL)

The proposed method was developed based on the original GB using FL to enhance the performance results of the original GB method and to reduce the number of parameter settings. In particular, the proposed method uses FIP, which can be defined as “a process of mapping from a given input to an output, using the theory of fuzzy sets” (Negnevitsky, 2005). Accordingly, the proposed method uses two input linguistic variables, namely,  $ql$  and average queuing delay ( $D$ ), to calculate a single output linguistic variable ( $DP$ ). The Mamdani-style FIP is applied to achieve this objective. The Mamdani method is one of the commonly used fuzzy inference techniques. It consists of four steps (Figure 3.8): crisp input fuzzification, rule evaluation, rule output aggregation, and defuzzification. These steps are implemented in the proposed method, and are discussed in detail as follows.

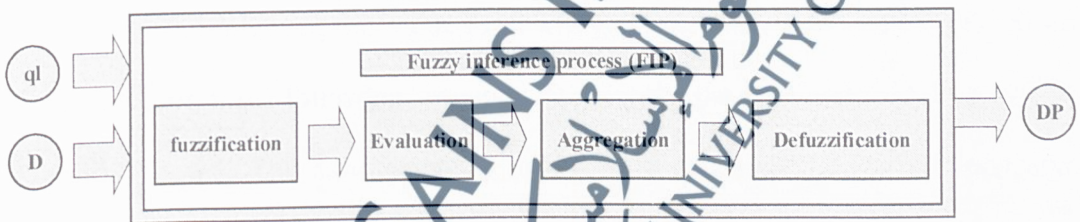


Figure 3.8: Fuzzy Inference Process

#### 3.6.1 Fuzzification

In this step, crisp inputs, which are  $ql$  and  $D$ , are processed to determine the degree to which these inputs belong to each appropriate fuzzy set. Every linguistic variable has its own Uod, which determines its range of values. The value of a fuzzy set is provided based on the behavior of a linguistic variable. The fuzzy sets for the inputs and output are as follows:

$ql = \{\text{conservative, middle, aggressive}\}$

$D = \{\text{few, medium, a lot}\}$

DP = {zero, low, moderate, high}

Every linguistic variable has its own Uod that clarifies its boundaries. The membership functions of the input linguistic variables (D and ql) and the output linguistic variable (DP) are presented in Figures 3.9–3.11. In general, many types of shapes can be used to represent a membership function based on the issues that should be addressed. For computational simplicity, linguistic variables are frequently represented by triangles or trapezoids. A trapezoid is used in the proposed GBFL technique. For the ql input linguistic variable, the Uod ranges from 0 to K, in which the significant value of ql is equal to K, and K represents the size of the router buffer. In addition, the Uod for the D input linguistic variable ranges from 0 to 2 K if the packet departure probability ( $\beta$ ) is 0.5. Assigning a 0.5 value to  $\beta$  can create non-congested and congested situations. Moreover, this value for  $\beta$  will yield the maximum value for D, which is 2 K. From the following equation  $D = mql/T$ , the maximum value of ql is K and  $T = 0.5$ . The assumption of membership functions for the DP linguistic variable is similar to those in Abdel-Jaber et al. (2008a). The boundaries of membership functions and fuzzy sets are selected by domain experts in the fields of FL and congestion control (Negnevitsky, 2005).

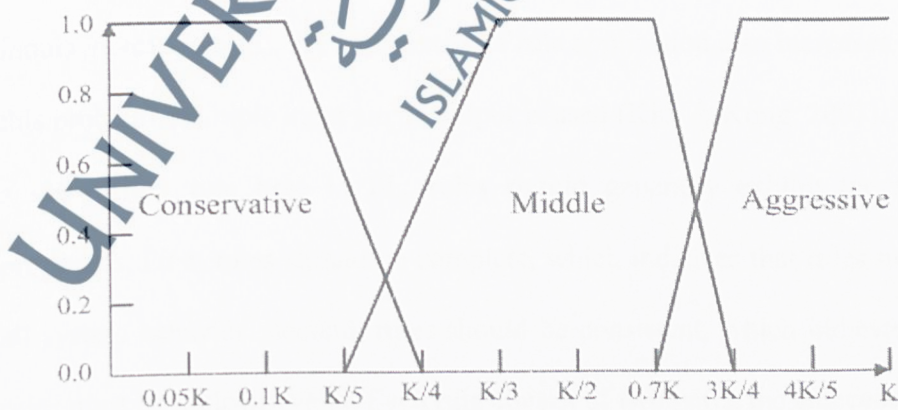


Figure 3.9: Memberships Function of ql.

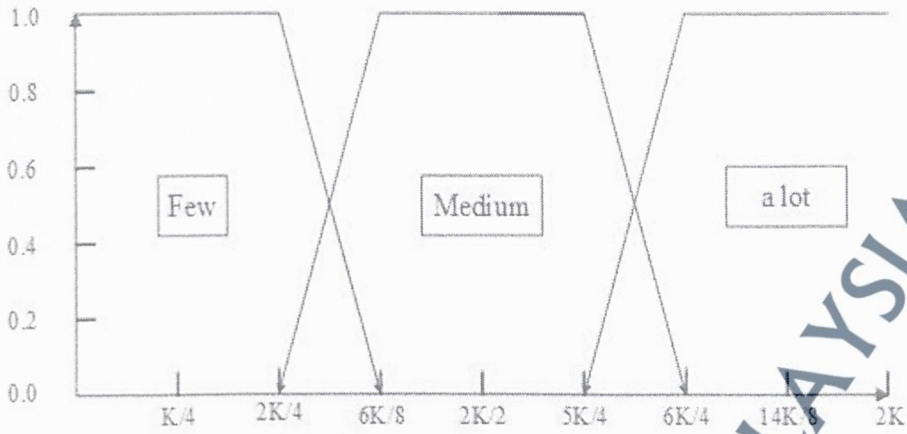


Figure 3.10: Memberships Function of D.

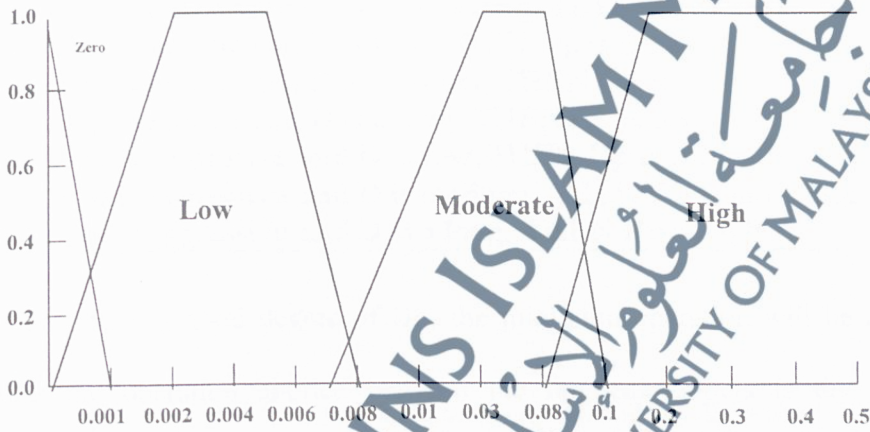


Figure 3.11: Memberships Function of DP.

### 3.6.2 Fuzzy Rule Evaluation

In this step, the fuzzified inputs are applied to the rules based on knowledge, which is created by domain experts. In general, when the number of inputs increases in FL, the complexity of rule application also increases. To solve this problem, multiple input single output is used (Kim & Kong, 2001). To obtain a satisfactory rule base in FL, rules should generally exhibit the following properties. First, rules should be complete, which indicates that rules must cover all system behavior. Second, rules should be consistent, which indicates that all rules must be logically valid. Each rule consist of two parts, the antecedent part of

fuzzy rules, which is represented by “if” (body rule), and consequent part (output). The antecedent part includes the input variables. Thus, the fuzzified inputs, together with their membership degrees, are applied to the first part to obtain the degree of membership in the consequent part. The rules are presented in Table 3.1.

Table 3.1: Fuzzy Rules for GBFL Based on ql and D.

FUZZY RULES
IF ql is conservative and D is few, THEN Dp is zero
IF ql is conservative and D is medium, THEN Dp is zero
IF ql is conservative and D is a long, THEN Dp is zero
IF ql is middle and D is few, THEN Dp is zero
IF ql is middle and D is medium, THEN Dp is zero
IF ql is middle and D is a long, THEN Dp is low
IF ql is aggressive and D is few, THEN Dp is zero
IF ql is aggressive and D is medium, THEN Dp is moderate
IF ql is aggressive and D is a long, THEN Dp is high

To obtain a good degree of DP, the minimum operation will be adopted because the operation applied between the linguistic inputs is the “AND” operation for all the rules. For example, suppose that the input crisp value is applied to rule number 8, which is “IF ql is aggressive and D is medium, THEN DP is moderate,” and the crisp value for ql is 0.8 and that for D is 0.5. In this case, the DP degree is equal to the minimum value between the ql degree and the D degree [MIN(0.8, 0.5)].

### 3.6.3 Rule Output Aggregation

In the previous step, a degree of membership is assigned to each consequent rule, and thus, combining all the outputs (membership values) from all the rules into a single fuzzy set is required. This process combines the inputs (list of membership values) with the single output (fuzzy set) for each output variable.

### 3.6.4 Defuzzification

The fourth step in FIP is to select a defuzzification method. The input for this step is the output from the previous step, which is a fuzzy set for every output linguistic variable, whereas the output from this step is a crisp value for each output linguistic variable. The defuzzification method derives the crisp value (numerical value) that represents the fuzzy value of the linguistic output variable. In the proposed method, the center of gravity (COG) is selected to find the numerical value of DP. COG is the most popular approach because it finds the point where a vertical line will divide the aggregate set into two equal masses (Negnevitsky, 2005). COG is expressed in the following formula (Negnevitsky, 2005):

$$COG = \frac{\sum_a^b \mu_A(Si) \times Si}{\sum_a^b \mu_A(Si)} \dots\dots\dots(3.22)$$

where  $\mu_A(S)$  is the membership function of elements  $Si$  in subset  $A$  and  $S$  represent the degrees of membership.

### 3.6.5 Router Buffer in the GBFL Method

Unlike the GB method, which reduces the number of parameter settings in the original BLUE, the proposed GBFL method (Figure 3.12) avoids using any parameter or threshold. The FIP for the GBFL method relies on two input variables ( $q$  and  $D$ ) to produce a single output variable (DP).

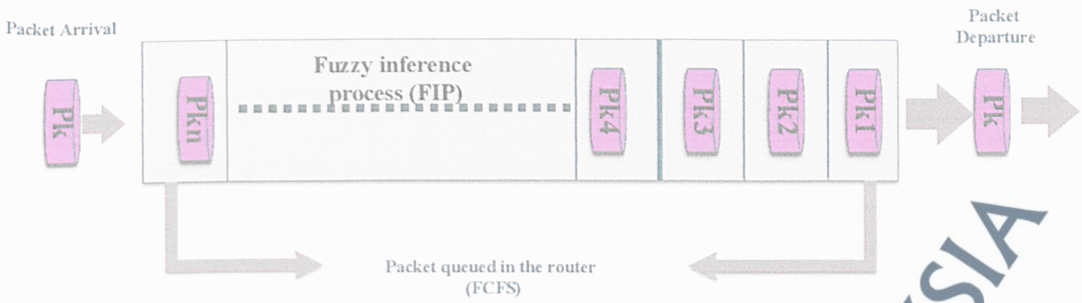


Figure 3.12: Single Router Buffer for the Proposed GBFL

In general, the first objective of GBFL is to avoid increasing the number of incoming packets at the router, and consequently, prevent the buffer from overflowing, which in turn, reduces packet delays and losses. In addition, the proposed GBFL aims to provide satisfactory performance results compared with the existing GB method and other AQM methods.

### 3.7 Performance Measures Matrixes

The following performance measures are used to evaluate the proposed GB method.

#### 3.7.1 Mean Queue Length (mql)

mql is defined as the measure for the average number of packets that can be presented simultaneously in the router buffer at any time. To reduce the possibility of congestion, the value of mql should be kept as low as possible to prevent the buffer from building up its size. mql is computed using Equation 3.23 (Woodward, 1993).

$$mql = \sum_{ql=0}^{ql=K} ql * P[ql] \dots \dots \dots (3.23)$$

where  $K$  represents buffer capacity, and  $P[ql]$  represents the probability of packet existence in a specific location in the buffer.

### 3.7.2 Throughput (T)

Throughput (T) is defined as the number of packets that have successfully passed through the router buffer per unit time, as shown in Equation 3.4. If the value of T is high, then the number of packets that passed is high. This condition prevents the router buffer from increasing the number of queued packets, and consequently, avoids congestion (Woodward, 1993).

$$T = (1 - P[0]) * \beta, \dots \dots \dots (3.24)$$

where  $P[0]$  represents the probability of the system being in an idle state which equal to  $\frac{c[0]}{\text{number of slot}}$ , and  $\beta$  represents the packet departure probability value and  $c[0]$  indicted the number of slots in which the router buffer is being empty.

### 3.7.3 Average Queuing Delay (D)

The average queuing delay (D) is defined as the average waiting time for each packet in the router buffer. Waiting time is the interval between packet arrival and packet departure. The value of D is calculated based on the values of  $mql$  and T by using Little's law (Woodward, 1993), as shown in Equation 3.25.

$$D = mql / T \dots \dots \dots (3.25)$$

Similar to  $mql$ , packets wait for a considerable amount of time in the router buffer if the value of D is increased, thereby increasing the number of queued packets in the router buffer and the possibility of congestion.

### 3.7.4 Packet Loss Probability Due to Overflow (PL)

PL probability is defined as the probability of PL due to router buffer overflow, as shown in Equation 3.26. No space is available for arriving packets when the router buffer overflows, and packet dropping will occur among the

newly arriving packets. Thus, PL serves as a good indicator of network performance (Woodward, 1993).

$$PL = (1 - \beta) * Pk, \dots\dots\dots (3.26)$$

where  $Pk$  represents the probability of a fully utilized system, and  $\beta$  represents the packet departure value.

### 3.7.5 Packet Dropping Probability (DP)

DP is defined as the probability value of dropped packets, which increases relatively with the development of congestion. DP is the probability of packets dropping before the router buffer is fully utilized. A low DP indicates good network performance (Woodward, 1993). The proposed GB DP is discussed in Section 3.3.

After the simulation architecture is built, the GB method is implemented to obtain the results of the performance measures.

## 3.8 Chapter Summary

In this chapter, two congestion methods are proposed, namely GB and GBFL. These methods aim at controlling the congestion at an early stage before the router buffers get overflowed and stabilizing the ql at specific value around threshold. The proposed GB method responds by using an unfixed and dynamically updating mechanism to decrease DP based on queue status. Meanwhile, GBFL method is proposed using an FL system. GBFL adopts ql and delay as input linguistic variables for an FL system to produce a single output (DP), which in turn, controls and prevents congestion at an early stage. Moreover, traffic modeling is an essential aspect of evaluating queue management methods. Queuing models, such as BP and MMBP, are used to evaluate the performance of AQM methods. BP fails to capture the

properties of multimedia traffic. Thus, MMBP-2 is used in this chapter to model traffic source and deal with the properties of burstiness and correlation. 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.

