A Comparison of Mamdani and Sugeno Fuzzy based Packet scheduler for MANET with a Realistic Wireless Propagation model

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Abstract: — The mobile nature of the nodes in a Wireless Mobile Ad-hoc Network (MANET) and the error prone link connectivity between nodes poses many challenges. These include frequent route changes, high packet loss, etc. Such problems increase the end-to-end delay and decrease the throughput. This paper proposes two adaptive priority packet scheduling algorithms for MANET based on Mamdani and Sugeno adaptive fuzzy logic. The fuzzy systems consist of three input variables: Data Rate, Signal-to-Noise Ratio (SNR) and Queue Size. The Fuzzy decision system has been optimised to improve its efficiency. Both fuzzy systems were verified using the MATLAB fuzzy toolbox and the performance of both algorithms were evaluated using the Riverbed Modeler (formally known as OPNET Modeler). The results were compared to an existing fuzzy scheduler under various network loads, for Constant-Bit-Rate (CBR) and Variable-Bit-Rate (VBR) traffic. The measuring metrics which form the basis for performance evaluation are end-to-end delay, throughput and packet delivery ratio. The proposed Mamdani and Sugeno schedulers perform better than the existing scheduler for CBR traffic; for Mamdani and Sugeno scheduler, the end-to-end delay was reduced by an average of 52 and 54% respectively. The performance of the throughput and Packet Delivery ratio for CBR traffic are very similar to the existing scheduler because of the characteristic of the traffic; the network was also at full capacity. The proposed schedulers also showed a better performance for VBR traffic; the end-to-end delay was reduced by an average of 38 and 52%, respectively. Both the throughput and packet delivery ratio increase by an average of 53 and 47%, respectively. The Mamdani scheduler is more computationally complex than the Sugeno scheduler, even though they both showed similar network performance. Thus the Sugeno scheduler is more suitable for real-time applications.

Keywords: Riverbed Modeler, VBR, CBR, SNR, MANET

1. Introduction

A MANET comprises of randomly distributed mobile nodes that constitute a network without the need of a control centre or infrastructure. MANET has many useful applications, e.g. disaster relief, military operation, and most recently civilian applications: this includes environmental monitoring, healthcare, etc. The transfer of data between MANET nodes is peer-to-peer in nature. A pair of mobile nodes can communicate directly when they are within the radio range of each other. Hence, in order for a particular source to transmit data to a destination outside of its transmission range; the data from the source node must be relayed through one or multiple intermediate peer(s). This phenomenon is called multi-hop, which is a special characteristic of the MANET.

As a result of the dynamic nature of node movement, there are frequent disconnections between nodes which are connected either directly or indirectly [1].

As MANETs gain popularity, the need for them to support real-time and multimedia applications has increased. These applications have Quality of Service (QoS) requirements and some of the measuring metrics include throughput, end-to-end delay and packet delivery ratio [2]. The QoS provision for a MANET can be provided over various layers in the Open Systems Interconnection (OSI) protocol stack, starting from the physical layer to the application layer. For example, the physical layer is responsible for the quality of transmission. The link layer handles the variable bit error rate. The change in the delay and bandwidth is the responsibility of the network layer. The transport layer deals with the delay and packet loss due to transmission, whilst the application layer handles the regular disconnection and reconnection of the network link [3].

The random nature of node movement in a MANET causes frequent route changes; this can lead to high packet loss and high end-to-end delay. It can also decrease the throughput of the network. As the traffic load increases, the performance of the network decreases. A MANET is infrastructure-less, thus it is difficult for any single mobile node to have an accurate and up to date picture of the network topology. In addition to the band limited shared network and the error prone nature of the wireless channel; the infrastructure-less state of the network makes meeting a specified QoS target more difficult to attain. All nodes in a MANET have the capacity to be a source, destination or just a relay. These various functionalities of a MANET node will create various queuing behaviour, which is different from a traditional cellular or wired network. Hence by using a scheduling algorithm to determine what queue or packet needs to be served next, the overall network performance can be improved. The default scheduling scheme for packets in MANET is First In, First Out (FIFO).

A great deal of research has been done to improve the QoS of MANET. Research papers such as [4] focused on routing protocols to improve link stability, end-to-end delay and bandwidth optimisation. Paper [5] proposed an efficient coding scheme for the dissemination of data between MANET nodes. Paper [6][7] compared the performance of various routing protocols with regards to mobility, delay, packet loss and network congestion and [8] discussed the link stability in MANET.

Paper [9] proposed a Mamdani fuzzy inference system with two input variables and a single output (Priority Index), to schedule packets in MANET. The two input variables are Channel Capacity and Data Rate; these were used to determine the Priority Index of packets to be scheduled. Paper [10] also presented some work on Mamdani fuzzy scheduling with MANET (based on buffer size and number of hops suffered by packet).

Based on [9] we explored a better ways to improve the QoS of MANET. In the course of this paper, [9] will be referred to by the first name of the first author 'Manoj'.

This work builds on [11] to propose a Sugeno based fuzzy scheduler. This scheduler is less computationally complex than the Mamdani. The performance analysis of the scheduling algorithms was done for Constant-Bit-Rate (CBR) and Variable-Bit-rate (VBR) traffic.

Packets are scheduled based on their Priority Index. The Priority Index for the individual packets is calculated by considering three input variables; these are Data Rate, Queue Size and Signal-to-Noise Ratio (SNR). The fuzzy scheduler was developed in a Riverbed Modeler using Proto-C language. The Mamdani and Sugeno fuzzy schedulers have since been optimised so that the algorithm runs quicker which is essential for real-time applications. The proposed schedulers improved the overall end-to-end delay, throughput and packet delivery ratio of the network.
This paper contains six sections; section 2 introduces the various traffic profiles, focusing on Constant Bit Rate (CBR) and Variable Bit Rate (VBR) traffic. Section 3 defines QoS and some of its measuring metrics; it also explains scheduling schemes and some currently available schemes. Section 4 describes the Fuzzy Inference System (FIS) focusing on the Mamdani and Sugeno FIS. Section 5 presents the performance analysis, it also includes the results and discussion; finally section 6 presents the conclusion.

2. Traffic Profiles

Traffic flow can be classified into one of the following traffic profiles: CBR, VBR and Bursty-bit-rate. This paper focused on CBR and VBR traffic because they model real-time applications for video, voice and control. These profiles are based on the inter-arrival times/distribution of the traffic [12].

2.1. Constant Bit Rate

The Data Rate for CBR traffic is shown in Figure 1, it does not vary over time. The average Data Rate and the peak Data Rate are the same for CBR models. The maximum burst size is also constant, thus the QoS requirement for this type of traffic is constant and easily predicted so the network can allocate the bandwidth needed for a flow [13]. This type of traffic is delay sensitive as it consists of real-time traffic; the odd packet drop is allowable as long as the packets are delivered in a timely manner. An example of this type of traffic is voice, video, control or any type of on-demand service [12] [13].

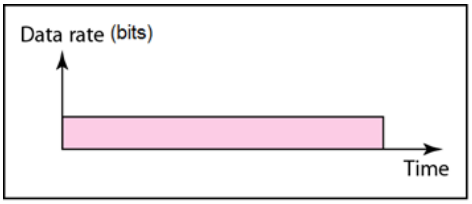

Figure 1: Constant Bit Rate

2.2. Variable Bit Rate

The data flow for VBR traffic is shown in Figure 2. It changes with time, and these changes are normally smooth, not sharp or sudden. The average Data Rate and the Peak Data Rate are different for this flow. This traffic type is more difficult for the network to handle, because the network cannot readily predict the resources needed for traffic flow. Examples of such types of traffic are compressed video and voice streams [12][13].

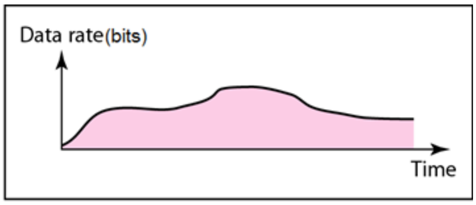

Figure 2: Variable Bit Rate

3. Quality of Service (QoS)

QoS is the network's ability to provide better service for selected traffic. The purpose for having QoS is to provide guarantees on the ability of the network to provide a certain service quality. The network features used to measure the QoS are delay, throughput and packet delivery ratio; these features are used as the measuring metric for performance analysis in this paper. Scheduling schemes can be used to improve the QoS of a network.

3.1. Scheduling Scheme

A scheduling scheme is required to improve the QoS of MANET. This is an algorithm that determines the order in which a thread or data flow can access the available resources. Packets from various traffic flows arrive at a node, and the scheduler prioritises individual flows in the queue so they are served fairly in order to improve the QoS. Some of the conventional available scheduling algorithms are FIFO, Priority Queuing (PQ) and Weighted Fair Queuing (WFQ) [14]: In FIFO: various packet flows are kept in the buffer until they are ready to be processed by the queue. Packets that arrived first at the queue are served first and any other packet that arrives afterwards will have to wait in the queue until all previous packets have been served. When the packet arrival rate is greater than queue processing rate, the queue will not be able to cope with the intensity of packet arrivals, thus congestion will occur. Hence packets will be discarded by the queue either because the queue buffer is already full or it has exceeded the waiting threshold in the queue. This conventional queuing scheme is not suitable for MANET because of the frequent changes of the network topology. Thus an adaptive queuing scheme which adapts to the network topology change is needed.

4. Fuzzy Inference System (FIS)

FIS is a system that implements human experiences and preferences with membership functions and fuzzy rules. It can be use as a general methodology to incorporate knowledge, heuristics or theory into controllers and decision making [10]. A fuzzy model is made up of four blocks; these blocks consist of a fuzzifier, defuzzifier, inference engine and fuzzy knowledge base as shown in Figure 3. The fuzzifier maps input from either a set of sensors or the network to linguistic variable between 0 to 1 using a set of input membership functions stored in the Knowledge Base. The inference engine applies reasoning to compute the fuzzy output using the 'IF-THEN' type fuzzy rules which are stored in the knowledge base, which is used to convert the fuzzy inputs to fuzzy outputs. The Defuzzifier converts the fuzzy outputs into a crisp value using an output membership function stored in the knowledge base.

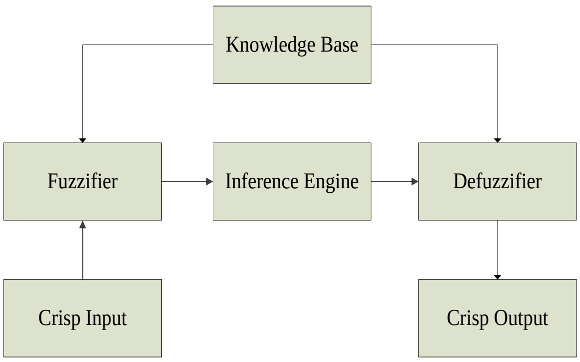

Figure 3: Basic Fuzzy System [9]

4.1. Fuzzy Scheduler

The proposed fuzzy schedulers have three input variables and a single output variable which is the Priority Index of the packet. These input variables contribute to the QoS performance of a network. The three inputs for the fuzzy model are SNR, Queue Size and Data Rate as shown in Figure 4. This is the Queue Size and Data Rate of the individual nodes the packet is associated with as well as the SNR of the receiver. The inputs are fuzzified, implicated, aggregated and defuzzified to obtain a crisp value which is the output i.e. Priority Index.

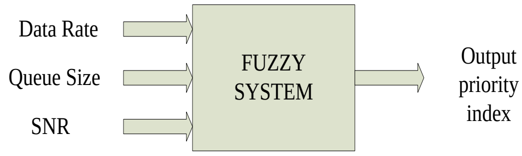

Figure 4: The inputs and outputs of the proposed Fuzzy Schedulers

4.2. Membership Function

There are a number of different membership functions, these include trapezoidal, triangular, piecewise linear, Gaussian and singleton. The most commonly used membership functions are trapezoidal, triangular and Gaussian Shapes. The type of membership function used can be context dependent and is chosen arbitrarily by the user depending on their level of experience [15]. The triangular and trapezoidal membership functions (MFs) was considered in this paper for its simplicity and low computational complexity. The linguistic variables associated with the input variables are Low (L), Medium (M) and High (H). The input membership function for SNR, Queue Size and Data Rate are shown in Figure 5 to Figure 7 respectively. The x-axis represents the particular fuzzy input and was normalised for all input variables. The y-axis represents the certainty level and it varies between 0 and 1. There are two ways of mapping MFs i.e., the number of MFs required for each input variable as well as the baseline. The first is knowledge elicited from experts in the field (manual mapping) and the second is knowledge extracted from trends in empirical data. The range of the fuzzy inputs on the x-axis was obtained through a combination of [9], educated assumption using simple queuing formulas as well as trial and error to maximize the overall system performance. This was carried out by running multiple test simulation models.

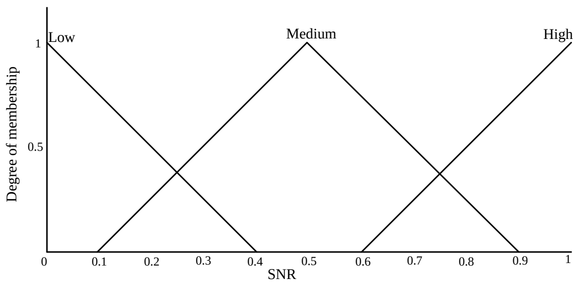

Figure 5: Membership function for SNR

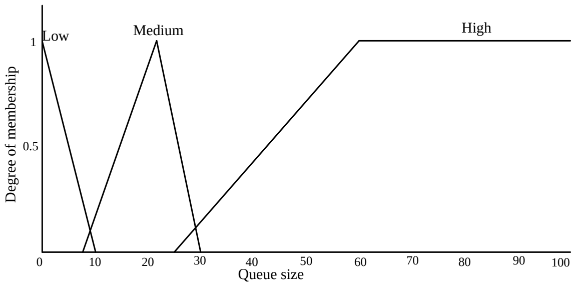

Figure 6: Membership function for Queue Size

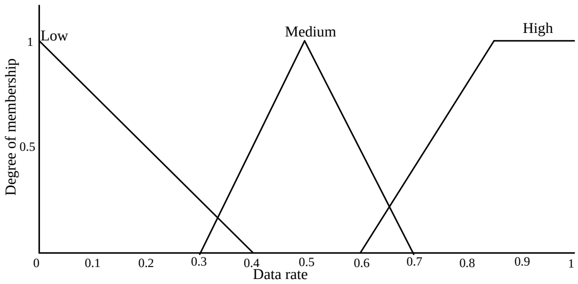

Figure 7: Membership function for Data Rate

The rules were carefully designed based on the relationship between the input variables. The conditional rules for the fuzzy scheduler are shown in Figure 8. The surface viewer which shows the relationship between the inputs and output is shown in Figure 9. The first rule can be interpreted as if (SNR is Low) and (Data Rate is High) and (Queue Size is High), then the Priority Index is Very Low. The other rules were formulated similarly. The output Priority Index ranges from 0-1, '0' meaning the highest priority in the queue and 1 the least priority. Thus as the Priority Index increases from 0-1 the packet priority in the queue drops accordingly. There are three input variables with three associated linguistic variables which gives 3^3 combinations, prompting the 27 rules.

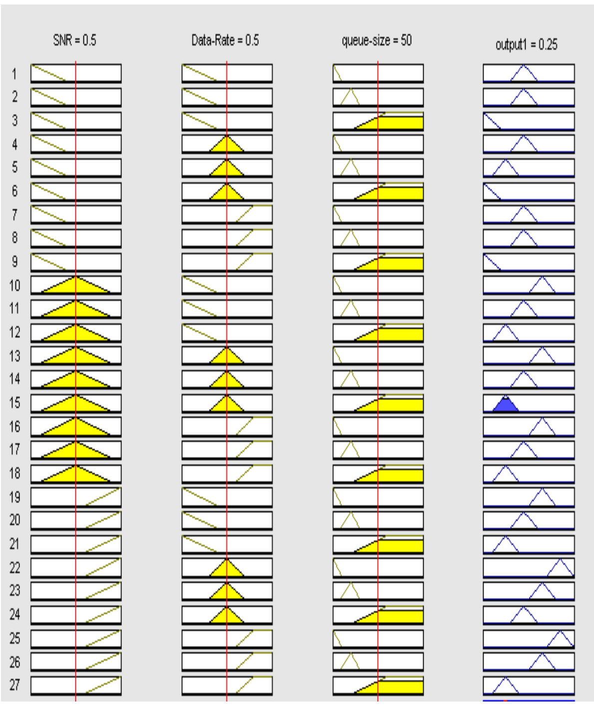

Figure 8: Membership Function and fuzzy rule base for the proposed schedulers

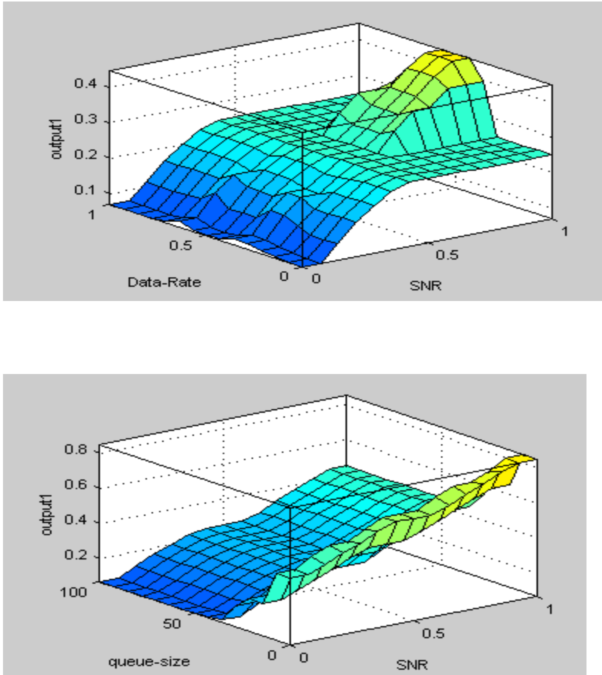

Figure 9: Surface viewer for Fuzzy Scheduler

4.3. Types of FIS

There are two major types of fuzzy system, the Mamdani [16] and the Sugeno [17]. The Mamdani and Sugeno FIS for a given system have the same number of inputs and membership functions. The rules are also the same; the only difference is the defuzzification of the fuzzy output. The next section highlights some of the variations between these two FIS systems.

4.3.1. Mamdani and Sugeno FIS Differences

The most fundamental difference between the Mamdani and Sugeno FIS is how the crisp output is generated from the fuzzy inputs [18]. Some of the most popular Mamdani defuzzification techniques are usually a variation of the Max Criterion Method. These include Smallest Of Maxima (SOM), Largest Of Maxima (LOM), and the Mean Of Maxima (MOM), these methods select the smallest, largest and mean output value for inputs whose membership value reaches maximum. MoM is one of the most popular methods; it calculates the final output 'Z' by averaging the set of output values that have the highest possibility degree 'M' using the formula given in equation (1)[19].

$$Z = \sum_{j=1}^{l} \frac{x_j}{l}, \quad x_j \in M \qquad (1)$$

Two other commonly used defuzzification techniques are the Center Of Gravity (COG)/Centroid and Center Of Area (COA)/Bisector method.

The COG/Centroid method determines the crisp output by calculating the center of gravity of the possibility distribution of the output. For continuous values, the output 'Z' is calculated using (2) [19].

$$Z = \frac{\int_{\mu} \mu(x) x dx}{\int_{\mu} \mu(x) dx} \quad (2)$$

The COA is similar to the COG method; however it calculates the position under the curve where the areas of both sides are equal. The COA can be calculated using (3) [19].

$$\int^{Z} \mu(x) dx = \int_{Z} \mu(x) dx \quad (3)$$

Braae et al. [20] presented a detailed analysis of various defuzzification techniques which include COG and MOM, they concluded that COG yields better results and for this reason, the COG/Centroid defuzzification technique was used in this work.

The output membership function for the Mamdani scheduler is made of triangular membership functions, it is shown in Figure 10. It consists of 5 linguistic variables; namely: Very Low (VL), Low (L), Medium (M), High (H) and Very High (VH).

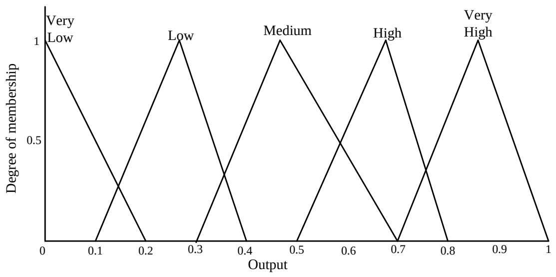

Figure 10: Mamdani Output Membership function

Sugeno FIS uses the weighted average to compute the crisp output and thus the complex iteration process used by Mamdani is bypassed. The Sugeno FIS does not have an output membership function. The output for Sugeno FIS is shown in Figure 11 and it is a constant value. It consists of five output points which are the same with the number of membership functions for the Mamdani output (Very Low (VL), Low (L), Medium (M), High (H) and Very High (VH)). The Sugeno FIS is a less computationally complex algorithm than the Mamdani equivalent. The interpretability and the expressive power of the Mamdani FIS are lost in the Sugeno FIS because the consequent of the rules are not fuzzy [19]. Meaning when the rules are evaluated the output will be a constant rather than a fuzzy set. Thus the impact of this on the system performance will be evaluated.

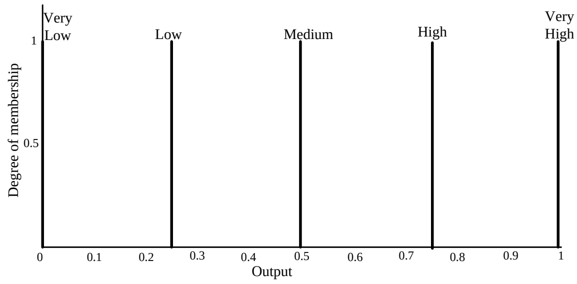

Figure 11: Sugeno Output Membership function

5. Performance Evaluation

The proposed fuzzy logic based packet scheduling algorithms are evaluated using a network simulation model called Riverbed Modeler and the measuring metrics are end-to-end delay, packet delivery ratio and throughput. The results are presented in this section.

5.1. Simulation Environment and Methodology

Riverbed Modeler is the leading simulation tool used in the academic circle for simulation of computer network and relevant technologies. It is used for modeling (designing) and analysing communication networks. It can model the performance of a network with a high degree of accuracy.

This simulation, models a network of 20 randomly distributed mobile nodes within a 500m x 500m area. The mobile nodes have wireless interfaces, which are configured to the IEEE 802.11n standard. A shadowing propagation model with path loss exponent (β) of 2.02 and a shadowing deviation (α) of 6.5 is used according to previously carried out outdoor experiment [21]. Each simulation is run for 600 seconds and multiple runs were carried out with varying seed values and the collected data was then averaged. The seed is used by the simulation's random number generator; multiple seed value will provide multiple instances of the traffic generated.

Table 1 shows the simulation parameters used. CBR and VBR traffic are generated and the performance of the scheduling algorithms is analysed. All mobile nodes served as a transmitter and receiver. The data payload is 1024 bytes [9]; the performance of the schedulers was evaluated under various load conditions 30, 40, 50 and 60 pkts/s. The random waypoint mobility model is used and the node speed ranges from 0-20m/s with a pulse time of 4s.

Table 1: Simulation Parameters

No. of Nodes	20
Area	500m x 500m
Simulation Time	600 sec
Mobility Model	Random waypoint
Speed of the nodes	0-20m/s
Propagation model	Shadowing model (β =2.02, α =
Traffic Type	CBR & VBR
Channel Bandwidth	12-54Mbps
Data payload	1024 bytes

MAC protocol	IEEE 802.11n (Buffer Size= 16MB)

5.2. Performance Evaluation of Fuzzy Scheduler

The inputs variables were obtained from the network and the fuzzy rules are evaluated based on these inputs. Each evoked rule has a corresponding output membership function. This output membership function is then implicated, aggregated and the crisp value (Priority Index) is calculated from these aggregated curves by using a Centroid defuzzification technique. The Proto-C language of Riverbed Modeler which implements the fuzzy system was verified using the fuzzy logic tool box in MATLAB.

5.3. Performance Evaluation using Riverbed Modeler

The output Priority Index of a packet is used to schedule the packet. By scheduling the packets this way, packets in highly congested queues are scheduled first. This differs from the standard priority scheduler because the packet Priority Index is based on individual packets rather than a traffic flow. If the queue of a node is full, it will cause an increase in the end-to-end delay and packet loss rate, thus newly arriving packets are discarded and packets in the queue that have exceeded the waiting threshold are discarded. The cause of the degradation of network performance is not limited to the length of the queue; it also relates to the Data Rate and SNR. When the SNR of the receiving node is low, the network will suffer a higher packet loss because of the poor wireless communication link between nodes. The packet priority increases as the SNR decreases in order to reduce the packet loss rate and thus improve the end-to-end delay.

The final input is the Data Rate; at higher Data Rates, the end-to-end delay of a packet is low and the packet delivery ratio is significantly higher. However when the reverse is the case, there will be a higher packet loss rate and an increase in the end-to-end delay. Packets are given a higher priority when the Data Rate is low. Packets present in a crowded node will experience a high queue delay and higher packet loss rate. This algorithm monitors these aforementioned parameters and calculates an appropriate Priority Index in order to optimise the network and improve the QoS performance. When a packet reaches a node, its Priority Index based on the network properties of that node is calculated and attached to its header. Each node has three sub-queues in order to reduce the effect of sorting on the overall network performance; arriving packets are en-queued in these sub-queues based on their Priority Index. The first sub-queue en-queues packets with Priority Index between 0-0.33; the second between 0.33-0.66 and the third between 0.66-1. The net result being that packets are sorted in the various sub-queues based on their Priority Index (i.e. Packets with the lowest Priority Index move to the head of the queue and are scheduled first).

5.4. Performance Analysis of Fuzzy Schedulers

This work is an extension of [11], which propose a Mamdani fuzzy base scheduler. In addition to the Mamdani, a Sugeno fuzzy based scheduler is also proposed. The Sugeno scheduler is faster than Manoj and [11] because it is less computationally complex and therefore more appropriate for real-time applications. The schedulers have varying degrees of complexity, hence the algorithms were run in Microsoft Visual Studio for 100 cycles, a timer is inserted at the beginning and end of each cycle to measure the duration, the average time was calculated.

The average time measured is equal to the additional processing delay both algorithms will add to individual packet per hop. This is added as a constant value to the formulae that calculates packet processing delay in Riverbed Modeler.

The algorithms were optimised by measuring the number of times each rules used by CBR and VBR traffic within the specified simulation parameters shown in Table 1.

These rules were optimized by using a counter to measure the number of times each rule is used by the simulation model. The result shows that only 10 of the 27 rules were used as shown in Table 2.

Table 2: CBR Rule Used count

Rules	**Count**
Rule 1	57
Rule 2	0
Rule 3	0
Rule 4	202551
Rule 5	24989
Rule 6	186714
Rule 7	0
Rule 8	0
Rule 9	0
Rule 10	0
Rule 11	0
Rule 12	0
Rule 13	271724
Rule 14	31477
Rule 15	310278
Rule 16	0
Rule 17	0
Rule 18	0
Rule 19	0
Rule 20	0
Rule 21	0
Rule 22	1512
Rule 23	85
Rule 24	852
Rule 25	0
Rule 26	0
Rule 27	0
Total	1030239

This was because CBR traffic consists of constant Data Rate. The 17 unused rules were eliminated; further optimisation is carried out with the 10 remaining rules. Two rules are found to have been used less than 200 times (Rule 1 and 23) and were also eliminated, reducing the total number of rules for the scheduler to 8. The performance of the optimised scheduler with 8 rules is compared with the performance of the scheduler with 10 rules. This is done by classifying the test into four cases as shown in Table 3.

Table 3: Test Case CBR

Case 1	Contains 10 rules
Case 2	Contains 9 rules - only rule 23 is removed
Case 3	Contains 9 rules – only rule 1 is removed
Case 4	Contains 8 rules - rule 1 &23 is removed

Table 4 shows the average delay, throughput and packet delivery ratio for all test cases. According to Table 4, there is no performance degradation for all test cases as all the results are the same. Hence the final number of rules for the CBR traffic is optimised from 27 to 8 without any performance degradation.

Table 4: Rule Optimisation results CBR

Cases	Delay	throughput	pdr
case 1	33.60	111538.90	0.37
case 2	33.60	111538.90	0.37
case 3	33.60	111538.90	0.37
case 4	33.60	111538.90	0.37

A similar optimization technique used for CBR is applied to VBR. All 27 rules were used by the VBR model, 3 of those rules (rule 20, 23 and 26) were used less than 200 times in the course of the simulation as shown in Table 5.

Table 5: VBR Rule Used count

Rules	Count
Rule 1	102324
Rule 2	14632
Rule 3	145251
Rule 4	81886
Rule 5	9626
Rule 6	89361
Rule 7	80126
Rule 8	8076
Rule 9	71367
Rule 10	130786
Rule 11	17515
Rule 12	192349
Rule 13	100258
Rule 14	11380
Rule 15	117355
Rule 16	96985
Rule 17	9612
Rule 18	93387
Rule 19	2881
Rule 20	186
Rule 21	1032
Rule 22	1929
Rule 23	117
Rule 24	655
Rule 25	2149
Rule 26	121
Rule 27	689
Total	1382035

The three aforementioned rules were eliminated, a series of simulations were carried out to check the performance degradation resulting from eliminating any or all of these 3 rules. The simulation work is classified into seven cases as shown in Table 6.

Table 6: Test Case VBR

Case 1	Contains 27 rules
Case 2	Contains 26 rules – only rule 20 is removed
Case 3	Contains 26 rules – only rule 23 is removed
Case 4	Contains 26 rules – only rule 26 is removed
Case 5	Contains 24 rules - Rule 20, 23 & 26 were removed
Case 6	Contains 25 rules - Rule 20 and 23 were removed
Case 7	Contains 25rules - Rule 20 and 26 were removed

Table 7 shows the results for the average delay, throughput and packet delivery ratio (pdr) for all test cases. The results showed no significant changes in the performance. Thus the fuzzy rule for the VBR traffic is optimised from 27 to 24 by eliminating all rules that were used less than 200 times.

Table 7: Rule Optimisation results VBR

Cases	Delay	throughput	pdr
case 1	32.93515	82462.04	0.276353
case 2	33.10667	82547.1	0.276452
case 3	33.00937	82479.36	0.276411
case 4	32.93515	82462.04	0.276353
case 5	33.09063	82553.96	0.276419
case 6	32.93515	82462.04	0.276353
case 7	33.00937	82479.36	0.276411

5.5. Performance Analysis of CBR Traffic

The service rate or capacity of the queue for the CBR model is 30pkt/s for all traffic loads. The average end-to-end delay for CBR traffic for load 30 and 40pkt/s are shown in Figure 12 and Figure 13 respectively. The proposed schedulers (Mamdani and Sugeno) perform better than the existing (Manoj). However as shown in Figure 12, the Sugeno scheduler performs slightly better than the Mamdani scheduler. The performance of the Mamdani and Sugeno scheduler are very close according to Figure 12 and Figure 13.

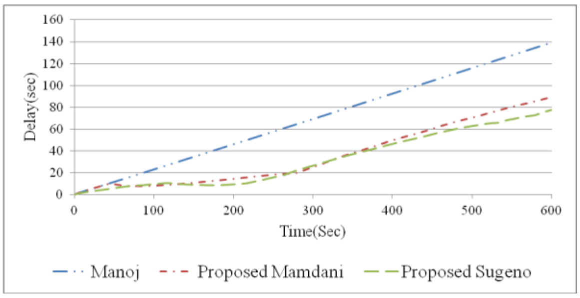

Figure 12: End-to-End delay for 30pkts/s CBR

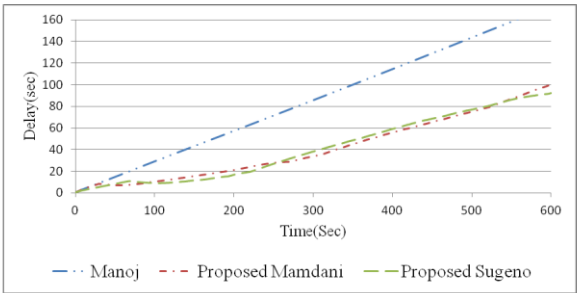

Figure 13: End-to-End delay for 40pkts/s CBR

The graph for the average end-to-end delay for 50 and 60pkt/s behave similarly to that of 30 and 40pkt/s. Table 8 contains the values for the average end-to-end delay for all traffic loads. According to Table 8, it can be noted that the proposed Mamdani and Sugeno scheduler performed better than Manoj. For traffic load 30 and 50pkt/s the proposed Sugeno performed slightly better than Mamdani whilst at 40 and 60pkt/s the proposed Mamdani performed slightly better.

Table 8: Average End-to-End delay CBR

Scheduler	**Average End-to-End delay (s)**			
	30pkt/s	***40pkt/s***	***50pkt/s***	***60pkt/s***
Manoj	69.43	86.11	99.75	109.00
Prop. Mamdani	35.92	41.11	46.54	49.96
Prop. Sugeno	32.03	41.36	42.04	49.98
Diff. Mamdani	33.51	45.00	53.21	59.04
Diff. Sugeno	37.40	44.76	57.71	59.02
%impr.Mamdani	**48.26**	**52.26**	**53.35**	**54.16**
%impr. Sugeno	**53.87**	**51.97**	**57.86**	**54.15**

The throughput and Packet delivery ratio for all traffic loads behave similarly. Their performances are very close because of the nature of the traffic being sent. The queuing capacity is 30pkt/s, thus the queue will forward packets at its maximum capacity for CBR traffic because all packets are of similar size. The throughput is approximately the same for all traffic loads as can be noticed from Figure 14 and Figure 15. According to Figure 15, the throughput for the Sugeno scheduler is slightly lower than that of Manoj and the proposed Mamdani at the initial stage of the simulation. This occurred between simulation times 0 to 80 seconds for 40pkts. The throughput becomes stable at 80 seconds simulation time.

The throughput for CBR traffic for all traffic loads are shown in Table 9. The throughputs for all the three schedulers are close. The negative sign shown in the table signifies Manoj performed better than the proposed, but it is by a small margin. At 60pkt/s load, the proposed Mamdani scheduler slightly outperforms Manoj by 0.509%.

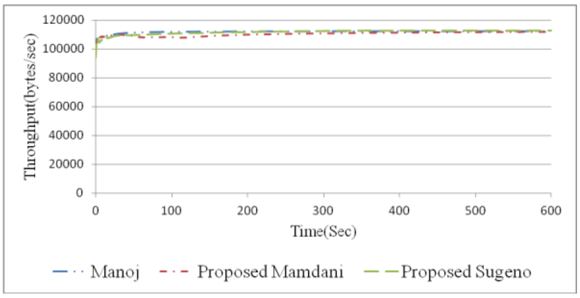

Figure 14: Throughput for 30pkts/s CBR

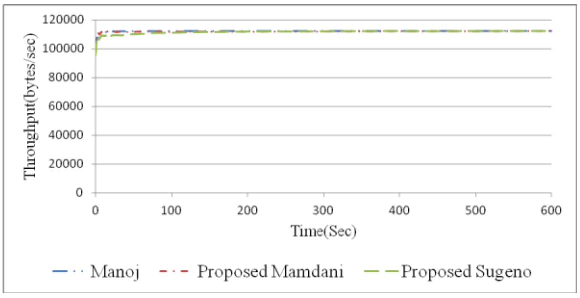

Figure 15: Throughput for 40pkts/s CBR

Table 9: Throughput CBR

Scheduler	**Throughput(bytes/s)**			
	30pkt/s	***40pkt/s***	***50pkt/s***	***60pkt/s***
Manoj	112011.8	112368.	112297.	110832.
Prop. Mamdani	110225.4	112095.	112097.	111397.
Prop. Sugeno	111505	111638.	111306.	110612.
Diff. Mamdani	-1786	-272.5	-199.7	564.4
Diff. Sugeno	-506.8	-729.4	-990.4	-220.6
%impr.Mamdan	**-1.595**	**-0.242**	**-0.178**	**0.509**
%impr. Sugeno	**-0.452**	**-0.649**	**-0.882**	**-0.199**

The service rate of the queue for all traffic loads is 30pkt/s. CBR traffic have the same data rate, as a result the queue will always forward packet at the maximum capacity for all traffic loads thus maintaining approximately the same throughput for all traffic loads.

The packet delivery ratio for 30 and 40pkts/s are shown in Figure 16 and Figure 17 respectively. The performance of the packet delivery ratio for all schedulers is approximately the same for all traffic loads. The packet delivery ratio for all loads is summarised in Table 10. According to Table 10, the packet delivery ratio decreases as the network load increases; this is a bottleneck effect. The Mamdani and Sugeno perform slightly better than Manoj.

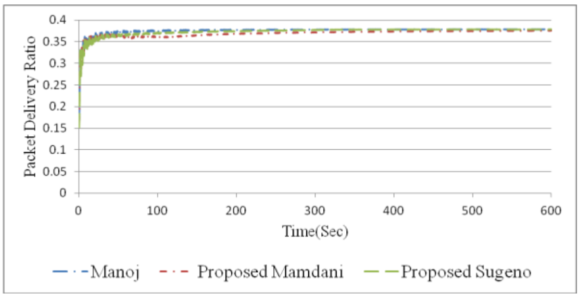

Figure 16: Packet delivery ratio for 30pkts/s CBR

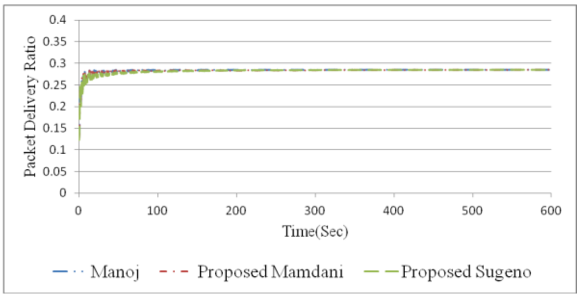

Figure 17: Packet delivery ratio for 40pkts/s CBR

Table 10: Packet Delivery Ratio CBR

Scheduler	**Packet Delivery ratio**			
	30pkt/s	***40pkt/s***	***50pkt/s***	***60pkt/s***
Manoj	0.195	0.125	0.093	0.073
Prop. Mamdani	0.276	0.191	0.147	0.116
Prop. Sugeno	0.277	0.188	0.140	0.108
Diff. Mamdani	0.082	0.066	0.054	0.043
Diff. Sugeno	0.083	0.063	0.046	0.035
%impr.Mamdani	**42.030**	**53.000**	**57.770**	**58.560**
%impr. Sugeno	**42.530**	**50.120**	**49.640**	**47.380**

5.6. Performance Analysis for VBR Traffic

The service rate of the queue for VBR model is 30pkt/s for all traffic loads. The performance analysis was done for the network under congested conditions. Hence the reason for the high queuing delays. The average end-to-end delay for the traffic generation rate of 30pkts/s is shown in Figure 18.

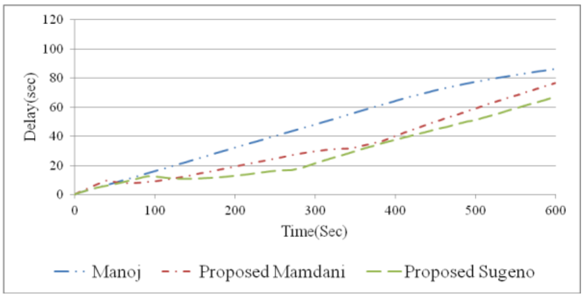

Figure 18: End-to-End delay for 30pkts/s

The proposed (Mamdani and Sugeno) scheduler performs better than the existing scheduler (Manoj). The performance of the Mamdani scheduler in the first 0-30 seconds is slightly higher than Manoj, whilst Sugeno scheduler is close to Manoj between this simulation time. Thus Manoj and Sugeno perform better than Mamdani between simulation times 0-30 seconds. The performance of the Mamdani scheduler, improves significantly as compared to Manoj from simulation time 30-600 seconds. The Sugeno scheduler also starts to improve significantly as compared to Manoj between simulation times 90-600 seconds; Sugeno also performs slightly better than Mamdani between simulation times 120-600 seconds.

The limited network resources cannot cope with the intensity of packets arrivals at the queue, thus congestion occurs. The average end-to-end delay increases linearly with time as shown in Figure 18. The behaviour of the delay graph for 40pkts/s is shown in Figure 19; it is similar to that of 30pkt/s in Figure 18. The end-to-end delay graph for 50 and 60pkts/s also shows a similar trait to Figure 18 and Figure 19. The values for the average end-to-end delay for all traffic loads are shown in Table 11.

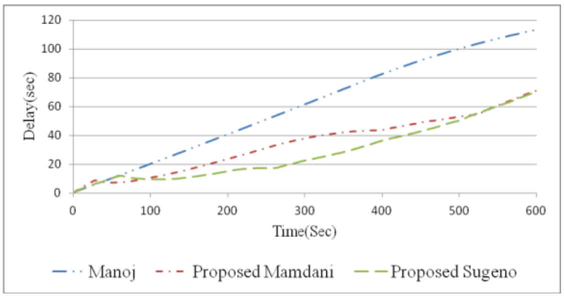

Figure 19: End-to-End delay for 40pkts/s

Table 11: Average End-to-End Delay

Scheduler	**Average End-to-End delay (s)**			
	30pkt/s	***40pkt/s***	***50pkt/s***	***60pkt/s***
Manoj	47.04	60.50	69.14	76.41
Prop.Mamdani	32.94	34.29	40.03	49.78
Prop. Sugeno	28.25	28.20	28.23	32.96
Diff. Mamdani	14.10	26.22	29.11	26.63
Diff. Sugeno	18.79	32.30	40.91	43.45
%impr.Mamdani	**29.98**	**43.33**	**42.10**	**34.85**
%impr. Sugeno	**39.94**	**53.39**	**59.16**	**56.87**

According to Table 11, the proposed scheduler (Mamdani) performs 29.98% better than Manoj for 30pkts/s, 43.33% better for 40pkts/s, 42.10% better for 50pkts/s, and 34.85% better for 60pkts/s. The performance of the algorithm (Mamdani) improves as the network load was increased from 30-40-50pkts/s but drops slightly at 60pkts/s. The proposed scheduler (Sugeno) also performs better than Manoj; an average percentage improvement of 39.94, 53.39, 59.16 and 56.87% for 30, 40, 50 and 60pkt/s, respectively. It also showed a better performance than the Mamdani scheduler for all traffic loads; as the traffic load increases from 30-40-50-60pkt/s, the performance of the Sugeno Scheduler as compared to Manoj and Mamdani improves. Thus appropriately combining input features such as the SNR, Data Rate and Queue Size, the proposed algorithms scheduled packets better than Manoj. When a network is congested, the gradient of the end-to-end delay graph gets steeper as more packets arrive at the queue and the network tends towards congestion.

Thus the gradient for the end-to-end delay graph shows the rate of increase of the network congestion. As the network load increases the gradient also increases. Therefore, to avoid congestion or prevent a severe case of congestion the gradient of the end-to-end delay graph needs to be prevented from increasing abruptly. The Manoj model becomes congested more quickly as shown in Figure 18 and Figure 19. The end-to-end delay graph for the proposed fuzzy schedulers (Mamdani and Sugeno) produced a lower gradient than Manoj, this was because incoming packet to the queue are given higher priority when the Queue Size is high, the SNR is low and the Data Rate is also low. These are the characteristics of the input variables when the network tends towards congestion.

The gradient for the end-to-end delay graph shown in Figure 18 for the Mamdani scheduler is 20.02% less than Manoj, whilst that of the Sugeno is 28.96% less than Manoj for the same load; thus the network congestion is reduced by 20.02 and 28.96% for the Mamdani and Sugeno respectively. At an increased load of 40 and 50pkts/s, the gradient for end-to-end delay for the Mamdani scheduler is 45.61 and 40.61% lower than Manoj respectively. The performance slightly dropped to 33.92% when the load was increased to 60pkts/s.

The gradient for the Sugeno scheduler at an increased load of 40, 50 and 60pkts/s is 46.60, 52.47 and 60.60%. Thus, it increases as the load increases, showing that the performance of the Sugeno scheduler improves as the load increases.

Figure 20 shows an improvement in the throughput for the proposed schedulers (Mamdani and Sugeno) for 30pkts/s and Figure 21 shows that of 40pkts/s.

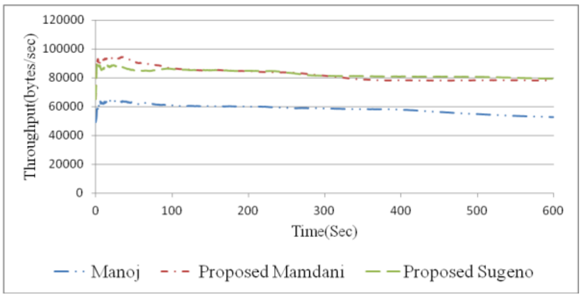

Figure 20: Throughput for 30pkts/s

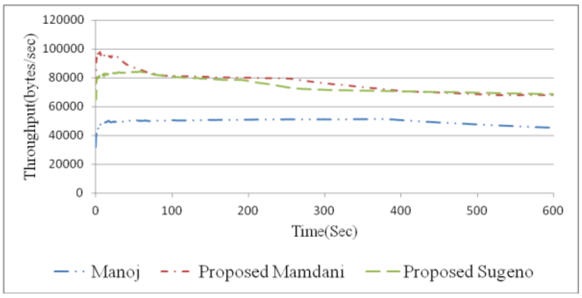

Figure 21: Throughput for 40pkts/s

The throughput for the proposed Mamdani scheduler and Sugeno schedulers are very similar for both 30 and 40pkts/s as shown in Figure 20 and Figure 21. Table 12 shows the percentage improvement of the throughput for the proposed schedulers (Mamdani and Sugeno) as compared to Manoj for all loads.

Table 12: Throughput

Scheduler	**Throughput (bytes/s)**			
	30pkt/s	***40pkt/s***	***50pkt/s***	***60pkt/s***
Manoj	58289.8	49540.7	46055.6	44113.8
Prop.Mamdani	82462.0	76370.5	72717.5	70058.5
Prop. Sugeno	82651.5	74395.5	68899.1	65389.3
Diff.Mamdani	24172.2	26829.8	26661.9	25944.7
Diff. Sugeno	24361.7	24854.8	22843.5	21275.5
%impr.Mamdan	**41.47**	**54.16**	**57.89**	**58.81**
%impr.Sugeno	**41.79**	**50.17**	**49.6**	**48.23**

The performance increases as the network load increases for the Mamdani scheduler. There was an increase of 41.47, 54.16, 57.89 and 58.81% for the throughput of the proposed Mamdani scheduler for 30, 40, 50 and 60pkts/s, respectively as compared to the Manoj. The percentage increases in throughput for the proposed Sugeno scheduler are 41.79, 50.17, 49.60 and 48.23% for 30, 40, 50 and 60pkts/s, respectively. The throughput of the proposed Mamdani scheduler showed is slightly higher than the throughput of the proposed Sugeno scheduler as shown in Figure 21. This is different from CBR traffic performance because of the variation in data rates of VBR traffic, thus the queue capacity might not be used at the maximum network load. CBR traffic maximizes the use of the available resources more than VBR traffic. Hence the scheduler increases the VBR throughput by maximizing the amount of traffic that can be forwarded from the queue in a second to make the network more efficient and also improves the network QoS performance.

Figure 22 shows an increase in the packet delivery ratio for the proposed schedulers (Mamdani and Sugeno) as compared to Manoj for 30pkts/s. The packet delivery ratio for 40pkts/s is shown in Figure 23. Table 13 shows that both proposed fuzzy schedulers perform better, thus resulting in a higher packet delivery ratio than Manoj.

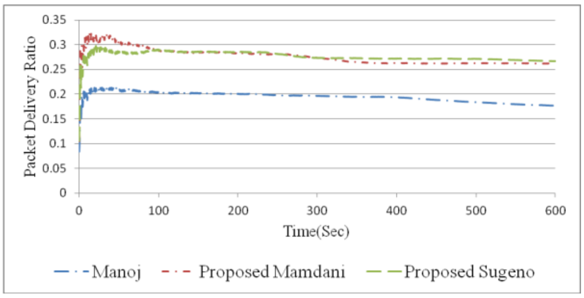

Figure 22: Packet delivery ration for 30pkt/s

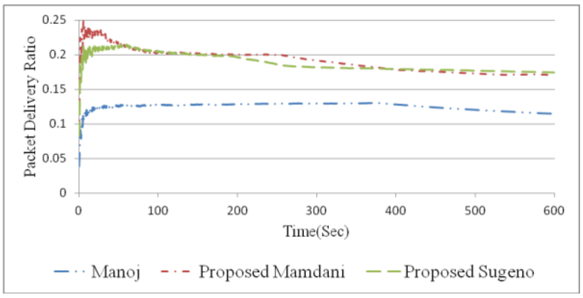

Figure 23: Packet delivery ratio for 40pkts/s

Table 13: Packet Delivery ratio

Scheduler	**Packet Delivery ratio**			
	30pkt/s	***40pkt/s***	***50pkt/s***	***60pkt/s***
Manoj	0.195	0.125	0.093	0.073
Prop. Mamdani	0.276	0.191	0.147	0.116
Prop. Sugeno	0.277	0.188	0.140	0.108

Diff. Mamdani	0.082	0.066	0.054	0.043
Diff. Sugeno	0.083	0.063	0.046	0.035
%impr.Mamdani	**42.030**	**53.000**	**57.770**	**58.560**
%impr. Sugeno	**42.530**	**50.120**	**49.640**	**47.380**

The percentage improvements of the packet delivery ratio for the proposed Mamdani scheduler as compared to Manoj are 42.03, 53.00, 57.77 and 58.56% for 30, 40, 50 and 60pkts/s, respectively; whilst the percentage improvement for the proposed Sugeno scheduler are 42.53, 50.12, 49.64 and 47.38% for 30, 40, 50 and 60pkts/s, respectively. The proposed scheduler delivered more traffic per second than the Manoj. The packet delivery ratio of the proposed Mamdani scheduler performs slightly better than the proposed Sugeno scheduler. The packet delivery ratio improvements are similar to throughput.

6. Conclusions

Two optimised fuzzy logic scheduling algorithms based on the Mamdani and Sugeno are proposed for the MANET. The performance of these schedulers was compared to an existing fuzzy scheduler. Both schedulers consider three inputs (Data Rate, Queue Size, and SNR) as opposed to the existing scheduler, which considered two inputs (Data Rate and Channel Capacity). The inputs to the fuzzy system were fuzzified, implicated, aggregated and defuzzified to obtain the crisp value. The crisp value ranges from 0-1 and it represents the packet Priority Index. Zero ‘0’ is the highest priority and one ‘1’ the least priority. Each node consisted of three sub-queues to reduce the effect of sorting on the network performance; individual packets are inserted in each sub-queue and served based on their Priority Index. The membership functions and the fuzzy rules were carefully designed. The number of rules has been optimised without affecting the performance of the CBR and VBR traffic.

The performance of the proposed scheduling algorithms (Mamdani and Sugeno) was analysed for CBR and VBR traffic. The measuring metric for performance analysis are end-to-end delay, throughput and packet delivery ratio.

The proposed algorithms perform better in terms of end-to-end delay for CBR traffic, whilst the throughput and packet delivery ratio are all very similar. This is because of the nature of CBR traffic, which consist of constant data rate at the entire simulation duration, thus the limited network load is utilised efficiently at high load.

The proposed schedulers perform better than Manoj in terms of end-to-end delay, throughput and packet delivery ratio for VBR traffic. The proposed Sugeno algorithm performs better than the Proposed Mamdani in terms of end-to-end delay whilst the throughput and packet delivery ratio for all traffic loads showed similar performance to the Proposed Mamdani scheduler.

Although the proposed Mamdani scheduler algorithm is more computationally complex than Manoj, it compensates for its complexity by optimally scheduling the network better than Manoj.

According to the simulation results, there is no significant difference between the performance of the Mamdani and Sugeno scheduler for VBR and CBR traffic, the Sugeno scheduler will be the better choice for real-time applications because of the simplicity of its design and it is less computationally complex.

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