Adaptive Congestion Control Under Dynamic Weather Condition for Wireless and Satellite Networks

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Abstract. Broadband satellite-based IP networks have been considered as the technology to enable a strong and promising next-generation market. In satellite communication systems, the channel performance might be severely degraded due to the dynamic weather conditions such as the precipitation, and thereby lead to network congestion. Therefore, congestion control is critical in such networks to satisfy QoS based Service Level Agreement (SLA). Moreover, the inherent large bandwidth-delay product of satellite channels impedes the deployment of existing numerous congestion control schemes. In this paper, we propose a modified Random Early Detection (RED) based congestion avoidance/control mechanism that incorporates a fuzzy logical controller to tune the queue thresholds of RED according to the dynamic weather conditions. We will show using analysis and simulations that the newly developed congestion control method is effective and efficient for broadband satellite-based IP networks.

Keywords: Satellite network, congestion control, active queue management, fuzzy logic.

1 Introduction

Due to extensive geographic reach, satellite communication systems are attractive for providing anywhere, anytime pervasive Internet access, especially in rural areas where the cost of alternative Internet access is high. In the satellite communications family, a new concept, broadband satellite networks have been proposed [1]. In the last few years, the broadband satellite network has gained tremendous research interest [2]. The broadband satellite network is IP-based and provides a ubiquitous means of communications for multimedia and high-data rate Internet-based applications, such as audio and video applications.

Dynamic weather conditions, such as the precipitation-caused channel fading, may severely affect the performance of satellite communications and thereby leads to network congestions. The congestion control is even more important in satellite communications networks due to the inherent large channel latency, or high bandwidth-delay product [3]. Therefore, similar to territorial IP networks, the network congestion control is critical in broadband satellite-based IP networks, for committing service-level-agreement (SLA) with regard to quality-of-service (QoS).

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Existing approaches for network congestion control in territorial IP networks reported in literatures cover a broad range of techniques, including window flow control [4], source quench [5], slow start [6], schedule-based control [7], binary feedback [8], rate-based control [9], etc. Recently, the active queue management (AQM) has been proposed to support the SLA QoS [10] and attracted much attention in the research community. AQM is a packet dropping/marking mechanism for router queue management. It targets to reduce the average queue length and thereby decrease the packet delay, while reduces the packet loss to ensure efficient network resource utilization. The most important and popular AQM mechanisms fall into two categories: Random Early Detection (RED) [11] and its variants, and Proportional Integral Derivative controllers (PID) [12]. PID mechanisms emerge from control theory and have better performance than RED in terms of the control of end-to-end delay. However, PID involves larger queue length oscillation, which leads to delay fluctuation (larger jitter). On the other hand, RED mechanisms are widely employed in today's IP routers, though they are often disabled by the users in the real world due to drawbacks such as the sensitivity to network configuration parameters and states, queue fluctuation, low throughout, etc [13]. Alternatively, the simple Drop-Tail scheme is applied as the *de facto* router queue management method.

Network congestion is caused by saturation of network resources, which is a dynamic resource allocation problem, rather than a static resource shortage problem. Such an optimal control problem of network resources is proven to be intractable even for the simplest cases [14]. The behavior of networks is usually highly non-linear, time varying, and chaotic (e.g., the observed self-similar traffic pattern [15]). Measurements on the state of networks are always incomplete, relatively poor and time-delayed for congestion control. Therefore, there is an inherent fuzziness in the network congestion control. In recent years, some fuzzy logic based mechanisms have been proposed for congestion control [16–20] in various territorial networks. In this paper, we propose an integrated RED-based congestion control mechanism using a fuzzy logic controller (FLC) with inference rules base. In this mechanism, the FLC tunes the RED queue thresholds to adapt to the change of weather conditions. Simulations show that it overcomes the drawbacks of original RED, such as the sensitivity to parameter configuration.

The remainder of this paper is organized as the following: Section II briefly introduces the background of RED and fuzzy logic, including membership functions and the inference rules base. Section III gives the architecture of our satellite-based IP network and the system design with the functional block diagram. In Section IV, we describe the simulation environment and scenarios for our system, in order to evaluate the newly developed congestion control mechanism: RED with fuzzy logic control (RED-FL). Finally, some conclusive remarks are listed in Section V.

2 Theory on RED and Fuzzy Logic

2.1 Random Early Detection (RED)

The key point of RED is to avoid network congestions by controlling the average queue length in a reasonable range. RED sets the minimum and maximum thresholds for queues and handle newly arrived packets according to the following rules:

1) if the queue length falls in the range from the minimum threshold ($q_{\min}$) to the maximum threshold ($q_{\max}$), then RED drops newly arrived packets with the probability that is calculated using exponential weighted moving average (EWMA) function;
2) if the queue length is larger than $q_{\max}$, then RED drops all newly arrived packets (i.e., Drop Tail)
3) if the queue length is smaller than $q_{\min}$, then no packet dropping;

RED was proven to be stable [21]. However its performance is sensitive to the dynamically parameter tuning, especially the tuning of $q_{\min}$ and $q_{\max}$. The efforts for accurately tuning the RED parameters achieved limited success so far. In this paper, we applied a fuzzy inference system (FIS) to the traditional RED scheme for parameter tuning, based on the inherent fuzziness in network congestion control. Especially, such a RED scheme with fuzzy logic control (RED-FL) is applied to making our satellite-based IP network more adaptive to the dynamic weather condition change, e.g., channel rain-fade.

2.2 Fuzzy Logic

Fuzzy Logic was first developed by L. A. Zadeh in 1965 to represent various types of "approximate" knowledge, which cannot otherwise be represented by crisp methods. Fuzzy logic is an extension of crisp two-state logic and it provides a better platform to handle approximate knowledge. Fuzzy logic is based on fuzzy sets and a fuzzy set is represented by a *Membership Function (MF).* A membership function is a curve that defines how each point in the input space is mapped to a membership value between 0 and 1. It provides the degree of membership within a set of any element that belongs to the universe of discourse (simply put the universal set). It maps the elements of the universal set onto numerical values within the interval [0, 1]. Specifically if X is the universe of discourse and the elements in X are denoted by x, then a fuzzy set A in X is defined as a set of ordered pairs.

$$\mathrm{A} = \{x, \mu_{\mathrm{A}}(x) \mid x \in \mathrm{X}\} \tag{1}$$

$\mu_A(x)$ is a membership function of x in A. The membership function maps each element of X to a MF value between 0 and 1. The membership function could be either piecewise linear or quadratic.The AND, OR, and NOT operators of Boolean logic exist in fuzzy logic as well. The Boolean logic is usually defined as the minimum, maximum, and complement. OR, AND and NOT are the so-called Zadeh operators since they were first defined as such in Zadeh's seminal papers. So for any fuzzy variables x and y:

NOT x = (1 - truth (x))
x AND y = minimum(truth(x), truth(y))
x OR y = maximum(truth(x), truth(y))

Fuzzy logic usually uses IF/THEN rules that are statements used to formulate the conditional statements that comprise the fuzzy logic. A single IF-THEN rule assumes the format of "*if x is A then y is B*". Where *A* and *B* are *linguistic values* and they are defined by fuzzy sets on the ranges X and Y (where X and Y are the universes of discourse). The if-part of the rule "*x* is *A*" is called the *antecedent* or *premise* and the then part of the rule "*y* is *B*" is called the *consequence* or *conclusion*.

3 Satellite-Based IP Network Model and Implementation

3.1 The Architecture of the Satellite-Based IP Network

The architecture of the satellite communication system for the project is depicted in Fig 1. In the architecture, all ground terminals communicate only with the central hub gateway, and vice versa. All communications must go through the relay satellite and the hub gateway. The satellite works as a channel relay. Bandwidth allocation algorithms may be required in both the hub gateway and ground terminals to maintain appropriate SLA QoS requirements. The bandwidth allocation granularity in the hub gateway is terminal-based while in ground terminals are user-based. Packet-switch is the main form of data communication running on our project of Intelligent Satellite System for Broadband Services (ISSBS), e.g., voice over IP (VoIP), video stream, and data (TCP/UDP), etc.

Fig 2 describes the functional block diagram for the high-level system design for our satellite-based IP network. The motivation of the design is to achieve high performance communications and congestion adaptation to impacts of dynamically weather change, on system performance (SLA QoS), e.g., channel rain-fade. Functional blocks of intelligent software in the system are defined as the following,

Hub Correlator
- Correlate relevant precipitation data with fuzzy inference engine to predict service degradation within specific timeframe
- Initiate appropriate proactive or reactive required actions

Link Detector:
- Assign traffic on forward and return link timeslots
- Adapted to fade & congestion

QoS Arbitrator
- Active queue management to discard packets/flows and notify impending network congestion

Traffic Shaper
- Connection admission control
- Packet conditioning and scheduling

3.2 Design of the Fuzzy Logic Controller (Fuzzy Inference System)

Fuzzy control uses the principles of fuzzy-logic based decision making to arrive at the control actions. A fuzzy controller is usually built of four units: Fuzzifier, Knowledge Base, Inference Engine and Defuzzifier, as shown in Fig 3.

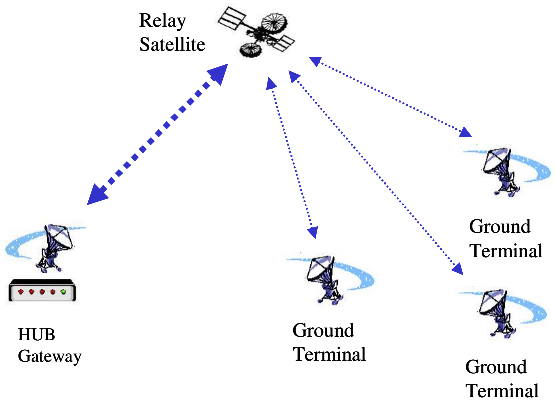


Fig. 1. The architecture of the satellite-based IP network

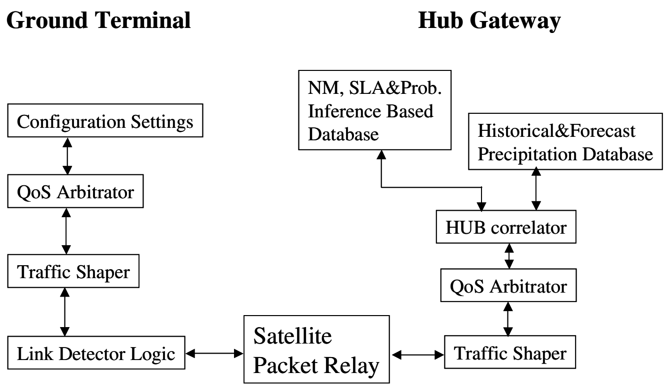


Fig. 2. Functional diagram of the satellite-based IP network

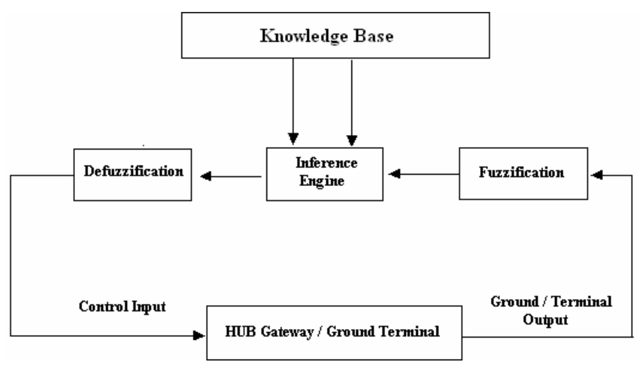


Fig. 3. Fuzzy Logic Controller showing the functional blocks

Fuzzifier **-** In the fuzzifier, crisp values are transformed into grades of membership functions for linguistic terms of fuzzy sets. The membership function is used to associate a grade to each linguistic term. In other words, the fuzzifier maps each of the crisp values of the inputs into its corresponding linguistic values, which may be viewed as the labels of fuzzy sets.

Knowledge Base (Fuzzy Rule Base) **-** The knowledge base contains domain-specific facts and heuristics that are useful to solve the domain related problem. They are represented in form of a set of linguistic control rules (IF-THEN rules) that characterize the goals and policies of the problem considered.

Fuzzy Inference Engine **-** This is the main "driver" of the Fuzzy Logic Controller and provides the decision-making logic to the system. It responds to the fuzzy input provided from the fuzzifier (also possibly previous inferences from the rule-base itself) and scrutinizes the knowledge base to identify one or more possible control actions or conclusions.

Defuzzifier - The control action of the Inference Engine encompasses a range of output values and is represented by membership functions. Defuzzification has to be done on this to resolve them into crisp non-fuzzy control signals. The most popular defuzzification strategy is the center of area method that yields a superior result.

In the design of our fuzzy logic controller for weather adaptation, three different scenarios (control problems) are dealt with:

1) Adjustment of the Bandwidth
2) Adjustment of the minimum queue length $q_{\min}$
3) Adjustment of the maximum queue length $q_{\max}$

The current weather conditions, allocated bandwidth and the queue length are the input parameters to the above control problems. The universe of discourse for the input and output parameters are assumed to be:

1) Bandwidth range (input in scenario #1) is selected to vary between 16 and 128 kbps per user. The packet size is fixed at 512 bytes.
2) The minimum queue length $q_{\min}$ (input in scenario #2) is varied between 4 and 16 packets.
3) The maximum queue length $q_{\max}$ (input in scenario #3) is varied between 8 and 20 packets.
4) Current weather condition (input in all cases) is based on the total precipitation rate.
5) The bandwidth adjustment (output in scenario #1) is done between 0 and 48 kbps per user.
6) The output parameters in scenarios #2 and #3 are adjusted to fall within the ranges already mentioned under 2) and 3).

The fuzzy sets associated with the input and output parameters are depicted in Fig. 4 and 5. The synthesis of the membership functions depend on the choice of thresholds of the weather condition parameters, e.g., the amount of precipitation. Such thresholds may be derived from historical data and empirical analysis. Also, the number of fuzzy sets for each weather parameter is flexible. In the design of our fuzzy logic controller for weather adaptation, we choose the triangular membership functions, which were proven to be extremely effective in territorial networks [19].

The fuzzy inference engine is built of numerous control rules that are fuzzy in nature and contain the linguistic variables associated with each input and output parameters.

Some of the sample rules for scenario #1 are listed below:

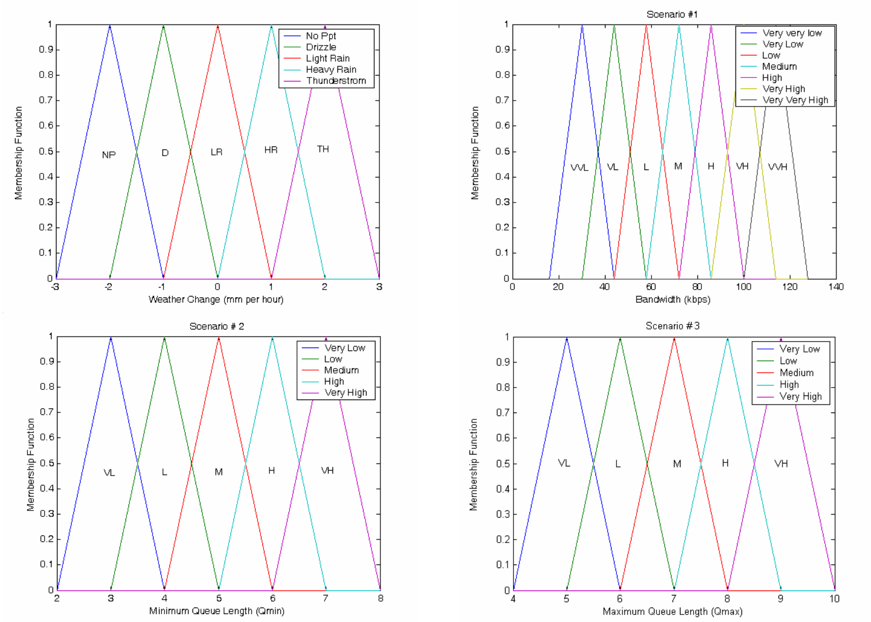


Fig. 4. Input parameters to the FIS (a) Change in current weather conditions (mm of rain drops/hour) (b) Scenario #1 where bandwidth ranges are shown (c) Scenario #2 where ranges of $q_{\min}$ are shown (d) Scenario #3 wherein ranges of $q_{\min}$ are shown

Scenario # 1 [Bandwidth Adjustment]

- *IF (the current allocated bandwidth is low) AND (weather becomes worse) THEN {heavily increase the bandwidth to commit the SLA QoS};*
- *IF (the current allocated bandwidth is medium) AND (weather becomes worse) THEN {slightly increase bandwidth to commit the SLA QoS};*
- *IF (the current allocated bandwidth is high) AND (weather becomes worse) THEN {do not change bandwidth};*

  ………..

Defuzzification converts the output fuzzy result into a crisp and a singular output. Center of area method, as mentioned in the earlier section is used as the defuzzification method.

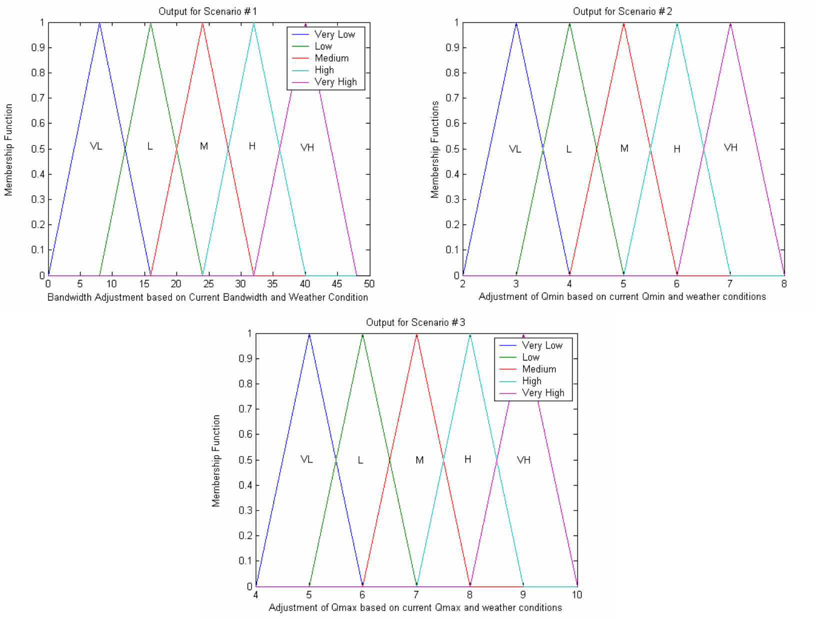


Fig. 5. Output parameters for the three control problems considered

4 Performance Evaluation

4.1 Simulation Setup

In order to evaluate the performance and robustness of our proposal, we map the architecture shown in Figure 2 into a simulation setup given in Figure 6, using the open source simulation tool NS-2.

Within the setup, two edge routers are deployed to simulate a ground terminal and the hub gateway, respectively. The intermediate node, relay satellite, is not really necessary for the setup but is included and reserved for the future use, e.g., IP routing and switching for multiple satellites. The link capacity between the edge router and the relay satellite is set to be 2 Mbps, which is typical for satellite links. The guaranteed minimum bandwidth for each session is 64 Kbps, and the bandwidth could burst up to the link capacity if all link capacity is not used.

In our satellite communication system, the traffic includes both TCP and UDP packets. In the research report, the traffic composition classified by protocols is as the following [23],

TCP: 83% of packets, 91% of bytes
UDP: 14% of packets, 5% of bytes

In our satellite-based IP network, due to the widely used video application, the percentage of UDP traffic is much higher than that in general Internet environment.

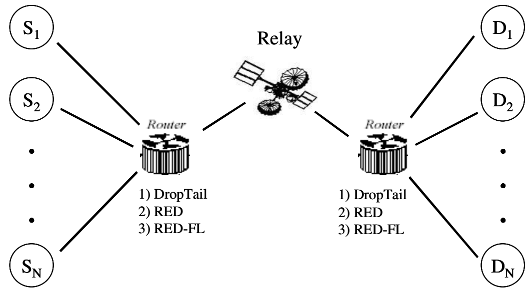


Fig. 6. Simulation setup for the satellite-based IP network

Therefore, we set half of the traffic be TCP and the other half UDP. The number of sessions is set to be 16/32/64 for various scenarios respectively. Note that the parameters of RED are set as recommended in [11].

4.2 Evaluation Metrics

With the system running, we monitor the instantaneous queue length for all scenarios. Also, the queue delays are measured and system throughputs are calculated for performance evaluation upon all scenarios. The dropping probabilities, which can be considered as the indicator of network congestion status, are also collected.

In addition to the inspection of RED-FL, we also implement the RED scheme as recommended in [11] and compare the performance of the two schemes in terms of the above performance metrics: instantaneous queue length, queue delay, dropping probability, and throughput.

4.3 Results and Analysis

A weather condition change pattern (precipitations in mm/time a.u.), where a.u. represents an arbitrary unit, is given in Fig. 7. Please note that the weather change is mapped into the change of TCP sessions. Since rain-fading effects cannot be reflected in the simulation directly, but an increasing channel fading can be considered equivalently as the increase of TCP session number. The corresponding simulation results of queue length, queue delay, packet dropping probabilities, as well system throughput, are collected from scenarios described above for both RED and RED-FL schemes. Figure 8 (a – d) compares the evaluation metrics for the two schemes. In the simulation, there are some TCP bursty sessions (to simulate the weather change) between the simulation time 0 to 20 second, and between 50 and 60 second. The bursty TCP sessions are obviously reflected in the instantaneous queue length, as well as 3 other metrics, in Figure 8. The packet size is fixed at 512 bytes.

The simulation results in Figure 8 show that all network congestion control methods we investigated in this paper have good performance in queue length, but the RED-FL improves the system throughput and packet dropping probabilities. Although it introduces somehow an increased queuing delay (Figure 8b), this queuing delay in RED-FL is more constant and stable.

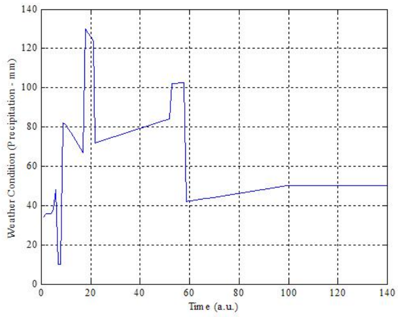
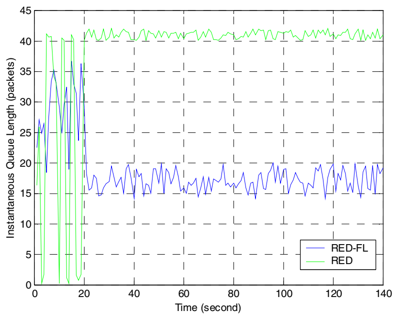
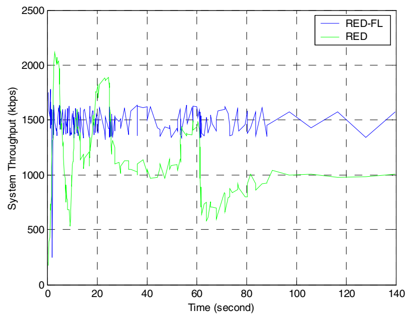


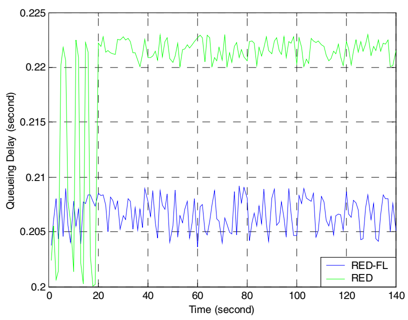
Fig. 7. Weather condition (Precipitation) change pattern



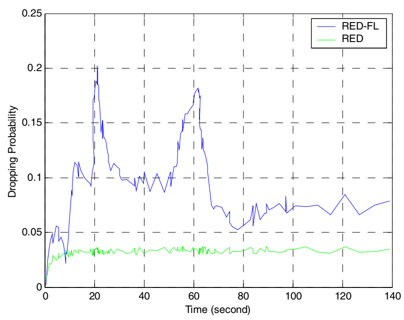
(a) Instantaneous queue length;



(b) Throughput;



(c) Queueing delay;



(d) dropping probability

Fig. 8. Simulation results

5 Conclusion

Broadband satellite-based IP networks have become more and more attractive for the construction of anywhere, anytime pervasive networking. However, due to the inherent impacts of dynamical weather change on system performance, e.g., channel rain-fading, intelligent network congestion control mechanisms are highly expected for such networks. In this paper, we introduced the architecture of broadband satellite-based IP network, together with the functional high-level design. A network congestion mechanism based on RED with the fuzzy logic controller is proposed for such satellite-based IP networks. Finally, the performance evaluation in terms of instantaneous queue length, queue delay, dropping probability, and throughput, is analyzed for the proposed RED-FL congestion control. The discussion implies that the newly proposed RED-FL is an effective congestion control method for satellite-based IP networks.

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