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A Pre-emptive Multiple Queue based Congestion Control for Different Traffic Classes in WSN

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Abstract*—Traffic in wireless sensor networks (WSN) exhibits a many-to-one pattern in which multiple source nodes send sensing data to a single sink node. Since bandwidth, processor and memory are highly constrained in WSN, packet loss is common when a great deal of traffic rushes to sink. The system must provide differentiated service to individual traffic classes. In this paper, a pre-emptive multiple queue based congestion control mechanism is proposed. To detect congestion and to provide QoS for high priority traffic multiple buffers are used. Using this mechanism, high system utilization, reduced packet waiting time, and reduced packet drop probability are achieved. An analytical model is developed to predict the performance of the proposed mechanism by calculating the performance measures including system throughput, drop probability of packets, and mean queue length. By comparing analytical and simulation results the effectiveness and accuracy of the model is demonstrated. Markovian process is used to develop the analytical model and *ns-2* for evaluating the performance of the mechanism.

Keywords: Wireless Sensor Networks, Quality-of-Service (QoS), Active Queue Management (AQM), Markovian Process (MP)

I. INTRODUCTION

Wireless sensor network has emerged as a promising technology because of the recent advances in electronics, networking, and information processing. Although WSN can be used in many applications there are a few constraints to overcome before it finally becomes a mature technology [11]. Some of the constraints are limited resources, bandwidth, higher bit error rates, lower throughput and longer delays compared to other networks. In WSN, the intrinsic features and limitations of sensor nodes, impose significant challenge for the reliable communication. The traffic characteristics and communication patterns in WSN are partial and vague. The traffic in WSN is very dependent on application scenario. Due to the development of different type of applications and different types of traffic in WSN, traffic congestion has become a critical problem and that can significantly degrade system performance and deteriorate the QoS for network. Congestion in WSN has negative impact on network performance and application objective, indiscriminate packet loss, increased packet delay, severe fidelity degradation [12]. Therefore, the employment of an effective congestion control mechanism in WSN is needed to guarantee the required QoS for various applications. Traffic in WSN can be mixture of real time, non-real time, periodic and aperiodic types. The QoS solutions developed for other networks cannot be directly ported to WSN because of its inherent characteristics.

Active queue management has been proposed as an efficient policy of congestion control to achieve high system utilization and low packet delay in networks with different type of traffic flows [13],[14]. The fundamental idea of AQM is to proactively drop the incoming packets before the occurrence of buffer overflow. In AQM schemes, to provide different QoS service for different traffic, priorities are used. There are two types of priority schemes, namely, inter-buffer priority and intra-buffer priority. In inter-buffer priority the arrival of different traffic classes enter their dedicated buffers. In the intra-buffer priority scheme, all traffic classes enter the same buffer, which is partitioned by some thresholds in order to provide differentiated loss priorities. In AQM schemes, performance advantage of two thresholds over single threshold is reported. Two thresholds can always be adjusted to give a lower delay for the same throughput. AQM coupled with priority schemes is able to provide better QoS differentiation as well as reduce traffic congestion and packet delay. Mathematical models are cheaper and easier to use than experimental or simulation applications, and also they can improve understanding of the real problem to set-up appropriate and flexible solutions that suit the network and design requirements. There are a few analytical models reported in the literature with limitations, which are able to handle priority systems integrated with the AQM congestion control policy in the presence of multiple traffic. Hence, in this paper a pre-emptive multiple queue based congestion control mechanism is proposed. This scheme uses different queues for different types of traffic and provides QoS requirements for High Priority (HP) packets.

Rest of the paper is organized as follows. Section II presents a literature review on the recent related work that concern with developing analytical models to evaluate the performance of RED algorithm considering its different performance characteristics. Section III describes the proposed AQM scheme in detail. The analytical model and numerical expressions for the performance characteristics are presented in Section IV. Simulation and analytical results are presented in Section V. Finally, in Section VI based on the obtained results conclusions are drawn and suggestions and recommendations for future work are pointed-out.

II. RELATED WORK

This section presents a literature review on the recent related work to develop analytical performance evaluation models for the existing queuing systems and algorithms. In particular related works on prioritized AQM and analytical models are discussed. Tin Qiu et. al [2] presents a evaluation method for packet buffer capacity of nodes using queueing network model, whose packet buffer capacity analyzed for each type node. The method is validated by the queueing network model with holding nodes for WSNs and designed approximate iterative algorithms. Mu Sheng-Lin et. al [3] developed a queuing model for RED queue management scheme to increase the transmission efficiency of multimedia over WSN. Lin Guan et. al [4] developed analytical framework for the performance evaluation of AQM mechanism based congestion control mechanism in WSNs in their paper three discrete time performance models with threshold based arrival rates, namely, one-step, two-step and linear reduction have been set to investigate how queue thresholds affect the whole system performance. Walenty Oniszizuk [5] studied and developed a Markovian Queuing scheme for multi server computer systems with two priority classes[low and high], partial buffer sharing schemes with thresholds and with blocking. Xiang-Lan Yin et. al [6] employed a priority-based queue management method to improve packet delivery ratio of more important packets. Geyong Min et. al [7] developed an analytical model for a buffer partitioned by a number of thresholds in order to provide differentiated loss priorities to individual traffic classes. Hussein Abdel-Jabed et. al [8] proposed a new analytical model based on DRED algorithm on two queue nodes queuing network. Lan Wang et. al [9] developed an analytical performance model for a finite capacity Queuing system with AQM mechanism on two thresholds. L Guan et. al [16] presented a Markov-Modulated Bernoulli arrival Process for the traffic arrivals for the performance evaluation of congestion control based on RED mechanism using queue thresholds. I. Awan et. al [18] presented a framework for the performance analysis of queuing networks with blocking under AQM mechanism. The analysis was based on a queue-by-queue decomposition technique. The use of queue thresholds is a well-known technique generalized exponential distribution which can capture the bursty property of network traffic. The analytical solution was obtained using the maximum entropy principle.

At this stage, it is important to realize that there are only limited numbers of references precisely concern with developing analytical models as most researchers use computer simulations or experimental tests in evaluating their systems or algorithms. It is observed that a fair amount of work has been done on designing analytical models on RED but not so great work on analytical models coupled with priority. It is also investigated that, analytical performance models of AQM coupled with priority mechanisms provide better QoS differentiation for multiple traffic, reduces traffic congestion and packet delay.

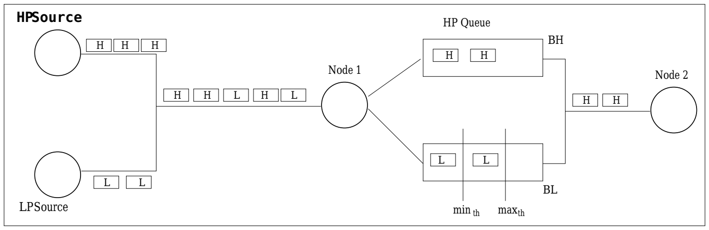

Fig. 1. Working of pre-emptive multiple queue

TABLE I
NOTATION TABLE

Notation	Meaning
BH	Capacity of HP Queue
BL	Capacity of LP Queue
$curqlhp$	Current quelength of HP Queue
$curqllp$	Current quelength of LP Queue
p	Drop probability
$\min_{th}$	Minimum threshold of LP Queue
$\max_{th}$	Maximum threshold of LP Queue

III. PROPOSED PRE-EMPTIVE MULTIPLE QUEUE CONGESTION CONTROL

In this section, the pre-emptive multiple queue congestion control mechanism is proposed. Different traffic types demand different packet delivery ratios and end-to-end delay. Vital messages always have a first priority with a minimum end-to-end delay. On the other hand, keep alive messages carrying small periodic data have relatively low priority which can tolerate to longer delay. To meet this demand, in this scheme multiple buffers with different priorities are used. Arrived packets are enqueued in respective priority buffers and will pre-empt the low priority (LP) packets if their buffer is full. The high priority (HP) packets are dropped only when both HP and LP buffers are full. Thus, providing higher throughput, lesser end-to-end delay and reduced drop probability for HP packets. LP packets are upgraded to HP packets if they are transient packets, and drop probability of LP packets depends on minimum and maximum threshold values of the LP queue. The threshold values are dynamically adjusted based on the total number of packets in the queues. The operation of the proposed AQM mechanism is depicted in Fig. 1. The packet drop probability of pre-emptive multiple queue buffer mechanism is given by:

$$P_{ij} = \frac{(i+j)-k+1}{max_{th}-k+1} \tag{1}$$

where, i = no. of packets in HP queue, j = no. of packets in LP queue, and k = average queue length

The packet drop probability of HP packets is given by:

$$P_{hp} = \begin{cases} 0 & \text{if curqlhp} < \text{BH} \\ 1 & \text{if curqlhp} = \text{BH } and \text{ curqllp} = \text{BH} \end{cases} \tag{2}$$

The packet drop probability of HP packets is given in Eq.

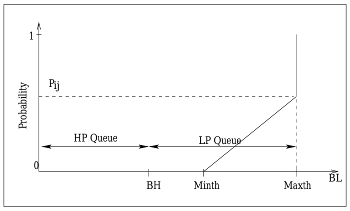

Fig. 2. Packet drop probability of HP packets

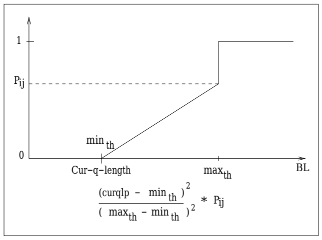

Fig. 3. Packet drop probability of LP packets

(2) and the interpretation of the equation is shown in Fig. 2. Drop probability is 1 only when HP and LP buffers are full otherwise it is 0. Similarly the packet drop probability of LP packets is given by:

$$P_{lp} = \begin{cases} 0 & \text{if curqllp} < \min_{th} \\ \frac{(curqlp - \min_{th})^2}{(\max_{th} - \min_{th})^2} & \text{if } \min_{th} < \text{curqlp} < \max_{th} \\ P_{ij} & \text{if } \max_{th} < \text{curqlp} < \text{BL} \end{cases} \quad (3)$$

The packet drop probability of LP packets is given in Eq. (3) and the interpretation of the equation is shown in Fig. 3. Drop probability of LP packets is 0 when queue length is less than min_{th} and the drop probability varies when queue length is between min_{th} and max_{th} and queue length is greater than max_{th}. The notations used in the Eqs. (1) - (3) are mentioned in Table I. The proposed pre-emptive multiple queue congestion control mechanism for multiple traffic is presented in Algorithms. 1- 4. Algorithm. 1 presents pseudo-code of Delete-Packet-From-Queue function of the proposed mechanism. This algorithm explains how packets are deleted from HP and LP queues. Packets are always deleted from HP queue and are deleted from LP queue only when HP queue is empty.

Algorithm 1: Delete-Packet-From-Queue

```
if BH = empty then
    Delete from front of LP Queue;
else
    Delete from front of HP Queue;
end
```

Algorithm. 2 explains pseudo-code of a function which assigns priority to packets. On the arrival of the packet, it is assigned high priority if it is a transient packet or real-time packet, otherwise, the packet is assigned lower priority.

Algorithm 2: Assign-Priority

```
if arrived-packet = trasient-packet or arrived-packet = real-time-packet then
    priority = high;
else
    priority = low;
end
```

Algorithm-3 describes HP-packet queue insertion procedure. HP-packet is inserted into HP queue and if HP queue is full it will pre-empt the LP packet from LP queue and insert the packet into LP queue.

Algorithm 3: Insert-Packet-HighPriorityQueue

```
if $curqlhp < BH$ then
    Insert-HPQ();
else
    if $curqlhp = BH$ and $curqllp = BL$ then
        Detete-end-LPQ(); Insert-front-HPQ();
    else
        Insert-Front-LPQ();
    end
end
```

Algorithm. 4 presents LP packet insertion is based on min_{th} and max_{th} values. It is inserted into LP queue with probability 0 when current queue length is less than min_{th} and inserted with drop probability $p1$ when the current queue length is between min_{th} and max_{th}. Inserted with probability $p2$ when current queue length is between max_{th} and BL. Values of $p1$ and $p2$ are mentioned in Eq. (3).

Algorithm 4: Insert-Packet-LowPriorityQueue

```
if $curqllp < min_{th}$ then
    Insert-LPQ();
else
    if $min_{th} < curqlp$ and $curqlp < max_{th}$ then
        Drop-packets-with-probability P1;
    else
        Drop-packets-with-probability P2;
    end
end
```

IV. ANALYTICAL MODEL

The analytical model using Markovian Process is formed for a dynamic buffer allocation policy and queue behavior under a priority service discipline. Each queuing system can be mapped onto an instance of a MP and then mathematically evaluated in terms of this process. MP can analyze the stationary and transient behavior of the network. To facilitate analysis and construction of an initial simplified model of our queuing mechanism, the assumptions imposed are as follows:

1) The events generated by WSN are assumed to follow Poisson process, and it is known that the sum of a number of independent tributary Poisson is also Poisson process. So inputs of different traffic sources follow Poisson distribution.

TABLE II
ANALYTICAL MODEL NOTATION TABLE

Notation	Meaning
λ	Arrival rate of packets
λ_1	Arrival rate of HP packets
λ_2	Arrival rate of LP packets
μ_1	Servicing time of HP packets
μ_2	Servicing time of LP Packets
P	PacketLoss
T	Throughput
L	Mean-q-length

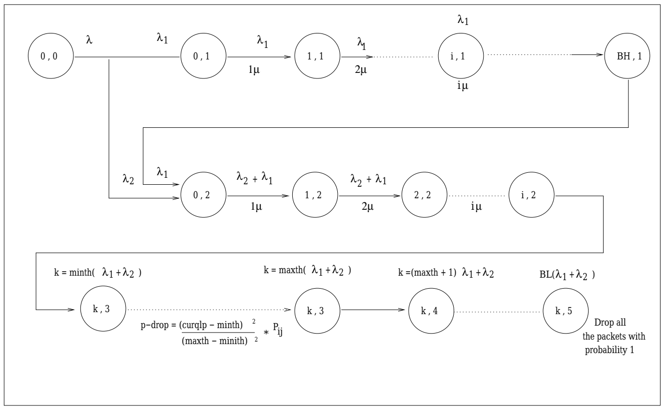

Fig. 4. State-transition diagram

2) The service time distribution is considered to be an exponential distribution.
3) The packets generated by different WSN applications have different priorities.
4) Network has a queuing discipline which maintains multiple buffers for traffic of different classes and serves HP buffers prior to other types.
5) Queuing discipline uses multiple buffers and use Drop-Tail mechanism for HP Queue and RED mechanism for LP Queue.
6) Buffers has the finite capacity BH and BL which are equal and with two dynamic threshold values min_{th} and max_{th}.
7) Packets of all priorities are assumed to be of same size.

Packets arrives to the system with an arrival rate of λ. Each node classifies the arrived packets into HP packets and LP packets if they are transient/real-time packets and locally generated packets respectively. Let arrival rate of HP packets and LP packets be λ_1 and λ_2 respectively. Let the service time of HP and LP packets be μ_1 and μ_2 respectively. Let the total system capacity be M. The packet dropping probability P_{lp} and P_{hp} are defined in Eq. (2) and Eq. (3) respectively. The dropping process can be seen as a decrease of the arrival rate with the dropping function. The maximum packets dropping probability of both the traffic classes is 1.

A state transition rate diagram of a two dimensional Markov chain of the queueing system with the AQM mechanism is shown in Fig. 4. All possible states of the queuing model and state transitions that occur among the states are shown in Fig. 4. A state is described by random variables (i, k) where, i represents number of jobs at service station, and k represents its state where $k = [0..5]$. The equilibrium state of the system for the arrival rates λ_1, λ_2 and service rates μ_1 and μ_2 is the ratio of arrival rate to the departure rate. If P_{ik} denote the joint probability of state (i, k) in two dimensional Markov chain, a set of linear equations are formed on analyzing the states of state transition diagram as shown in Fig. 4. These set of linear equations represents the transition equilibrium between incoming and out-going streams of each state. Using these set of equations, the desired performance characteristics such as mean queue length (L), as in Eq. (10) throughput (T), as in Eq. (11) and probability of packet loss (P) as in Eq. (12) are obtained. The notations used to derive the analytical model is presented in Table II. The Eqs. (4) - (9) represents different state equilibrium equations.

The expressions for the aggregated system performance metrics like mean queue length L and throughput T are derived by utilizing the characteristics of traditional M/M/1 queueing system. The packet loss probability consists of the probability of packet loss when the queue is full and that of packet dropping before the queue becomes full. Probability of packet loss depends on mean response time and mean waiting time in the queue and are derived using Little's Law and hence packet loss probability P expression is derived. Eq. (4) reveals that arrival and departure equilibrium of the system in the 0^{th} state.

$$(\lambda_1 + \lambda_2) \cdot P_{0,1} = (\mu_1 + \mu_2) \cdot P_{1,1} \tag{4}$$

Eq. (5) presents the arrival and departure equilibrium of the system in the i^{th} state.

$$\begin{aligned} (\lambda_1 + \lambda_2 + i.(\mu_1 + \mu_2)) \cdot P_{i,1} \\ = (\lambda_1 + \lambda_2) \cdot P_{i-1,1} + (i+1) \cdot (\mu_1 + \mu_2) \cdot P_{i+1,1} \end{aligned} \tag{5}$$

Eq. (6) represents the arrival and departure equilibrium of the system in the i^{th} state where mean queue length is less than min_{th}.

$$\begin{aligned} (\lambda_1 + \lambda_2 + c \cdot (\mu_1 + \mu_2)) \cdot P_{i,1} = \\ (\lambda_1 + \lambda_2) \cdot P_{i-1,1} + \\ c \cdot (\mu_1 + \mu_2) \cdot P_{i+1,1} \end{aligned} \tag{6}$$

The arrival and departure equilibrium of the system in the i^{th} state where average queue length is between min_{th} and max_{th} is shown in Eq. (7).

$$\begin{aligned} (\lambda_1 + \lambda_2 + c \cdot (\mu_1 + \mu_2)) \cdot P_{c+\min_{th}+1,1} \\ = (\lambda_1 + \lambda_2) \cdot P_{c+\min_{th}-1,1} + \\ c \cdot (\mu_1 + \mu_2) \cdot P_{c+\min_{th}++1,1} + c \\ \cdot(\mu_1 + \mu_2) \cdot P_{c+\min_{th}++1,2} \end{aligned} \tag{7}$$

Eq. (8) represents the arrival and departure equilibrium of the system in the i^{th} state where average queue length is between max_{th} and M.

$$(\lambda_2 + c.(\mu_1 + \mu_2)) \cdot P_{c+\max_{th},1} = (\lambda_1 + \lambda_2) \cdot P_{c+\max_{th}-1,1} \tag{8}$$

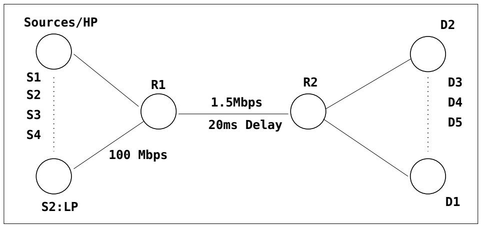

Fig. 5. Network topology used for simulation

Eq. (9) presents the arrival and departure equilibrium of the system in the i^{th} state where average queue length reaches M.

$$(\lambda_1 + \lambda_2).P_{0,1} = (\mu_1 + \mu_2).P_{1,1} \tag{9}$$

The mean queue length L can be expressed from the equilibrium joint probability P_{ij} as

$$L = \sum_{i=1,j=1}^{M} (P_{ij} \cdot i \cdot j) \tag{10}$$

The throughput T is calculated by considering the drop probability of HP and LP packets respective to their arrival rates, as given below.

$$T = \sum_{i=1,j=1}^{M-1} (P_{ij} \cdot (P_{lp} \cdot \lambda_1 + P_{hp} \cdot \lambda_2)) \tag{11}$$

Similarly the packet loss P is derived by considering packets (both HP and LP) staying in the system at their respective arrival rates, as given below.

$$P = \sum_{i=1,j=1}^{M} P_{ij} \cdot \frac{(1 - P_{lp}) \cdot \lambda_1 + (1 - P_{hp}) \cdot \lambda_2}{\lambda_1 + \lambda_2} \tag{12}$$

V. SIMULATION

A simple bottleneck network topology is considered for simulating the proposed mechanism. The network consists of two routers $R1$ and $R2$, with n multiple traffic generating sources and n logically connected destinations. The bottleneck link between $R1$ and $R2$ is assumed to have a link speed of 1.5Mbps and propagation delay 20ms. All other connections are connected to routers $R1$ and $R2$ with each link 100Mbps bandwidth. The propagation delay for other links is generated randomly. Packet size of 1500 bytes is considered. Two types of traffic flows namely real time and non-real time are considered. The results are tested for both DropTail and pre-emptive multiple queues. The simulation time specified is up to 100 sec. Simulator *ns-2* is used for simulation of proposed AQM mechanism

Fig. 6. presents the packet drops recorded in DropTail is relatively higher than proposed AQM mechanism. This is due to multiple buffers used for different traffic classes. Fig. 7. shows that for a prioritized application HP packet drops are less in proposed AQM mechanism than LP packets. This is because, HP packets acquire more bandwidth, wherein DropTail mechanism both HP and LP packets share same bandwidth. Fig. 8. exhibits HP packets have higher throughput in proposed AQM mechanism than DropTail, because HP packets are handled crucially. Fig. 9. presents LP packets drop of proposed AQM mechanism is more than DropTail, because in the proposed mechanism LP packets are victimized wherein DropTail mechanism both the traffic are handled with equal priority. It is observed in Fig. 10. that throughput of LP packets in DropTail is more than throughput of LP packets in proposed mechanism because LP packets retransmission is more in proposed mechanism. Fig. 11 depicts energy consumption in proposed mechanism is less than DropTail since retransmission of packets is less. Even though LP packets are dropped, total packet drops is less than DropTail. Thus the mechanism results in minimum retransmission and less energy consumption. Fig. 12 states that end-to-end delay for HP packets is less in proposed mechanism due to more buffer occupancy and priority given to HP packets.
The analytical results are presented in Figs. 13 - 15. The initial values for the parameters considered are as follows: λ_1= 1.6, λ_2 = 1.4, μ_1 = 0.2, μ_2 = 0.2, min_{th} = 5, max_{th} = 15, BL = 35 and BH = 35, $packetsize$ = $150bytes$, $Data - rate - of - all - traffic - sources$ = $100Mbps$, link $R1$ and $R2$ = $1.5Mbps$.

It can be inferred from Fig. 13 that the mean queue length decreases as the number of connection increases. This result is reflected in both numerical and simulation experiments. Fig. 14 reveals that the packet loss increases as number of FTP connections increases. This result is supported by results of both numerical and simulation experiments. Fig. 15 presents that the throughput value gradually increases to the number of connections. Simulation and numerical results recorded are presented in Table III.

VI. CONCLUSION

In this paper, a pre-emptive multiple queue based congestion control mechanism for multiple traffic is proposed. The proposed mechanism is simulated using $ns - 2$ by considering different traffic classes with same packet size and queue length. Simulation results shows that the proposed mechanism outperforms the DropTail AQM mechanism in terms of packets drop, throughput, end-to-end delay and energy consumption. LP packets are victimized in this mechanism by providing less bandwidth over HP packets. An analytical model for the proposed mechanism is developed and numerical results are compared with the simulated results for the parameters mean-queue-length, throughput, and packet-loss. In this mechanism, dynamic thresholds for drop probability is considered, however, it can be extended to arrival rate adjustment. Also, the network size, topology, queue length and packet size can be varied to obtain results in different scenarios.

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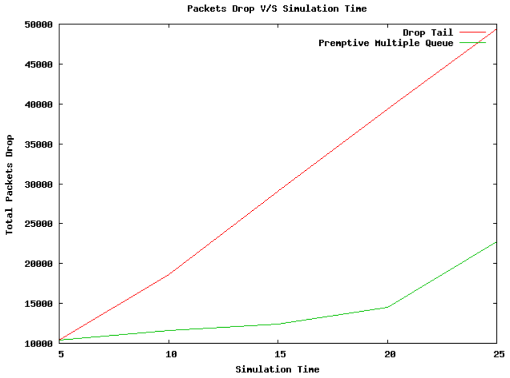

Fig. 6. Comparison of two AQM mechanisms on packets drop

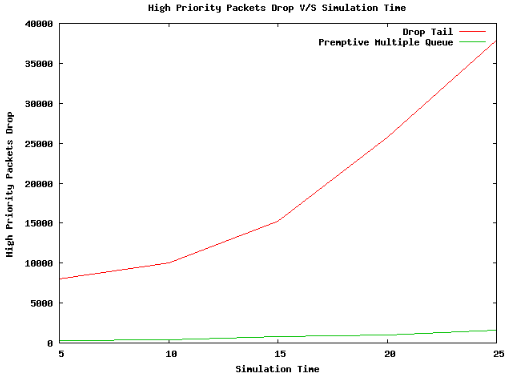

Fig. 7. High priority packets drop with two AQM mechanisms

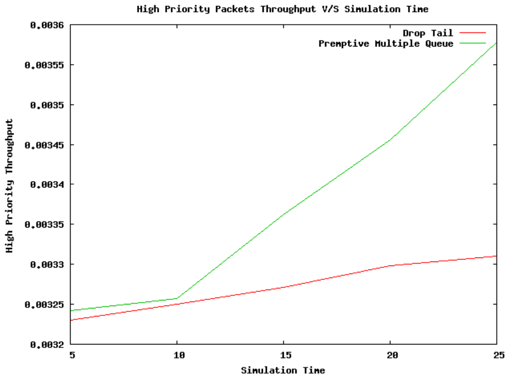

Fig. 8. Throughput of HP packets in two AQM mechanisms

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No.of FTP Connections	S-Avg-Q-Length	N-Avg-Q-Length	S-Packet-Loss	N-Packet-Loss	S-throughput	N-Throughput
5	13.538	13.508	0.22	0.26	8510	8492
10	13.216	13.200	0.23	0.29	9105	9099
20	12.799	12.790	0.25	0.31	9181	9177
30	12.214	12.220	2.08	2.14	9188	9175
40	11.436	11.441	5.67	5.72	9133	9129
50	10.418	10.425	8.60	8.65	9083	9078

TABLE III
COMPARISON OF NUMERICAL AND SIMULATION RESULTS

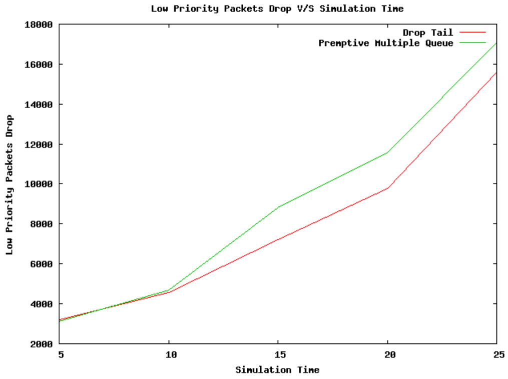

Fig. 9. Low priority packets drop in two AQM mechanisms

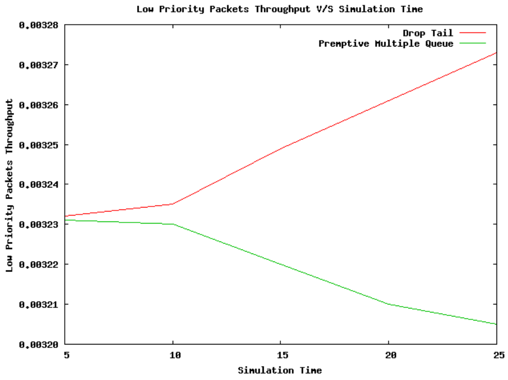

Fig. 10. Throughput of LP packets in AQM mechanisms

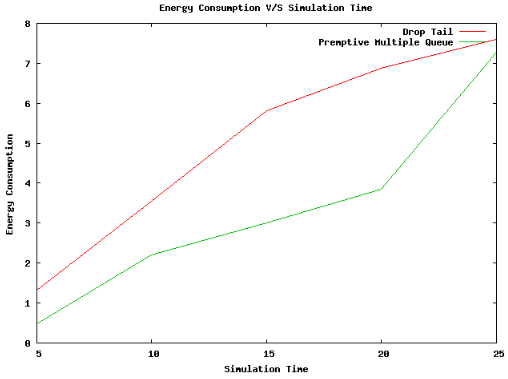

Fig. 11. Energy consumption of AQM mechanisms

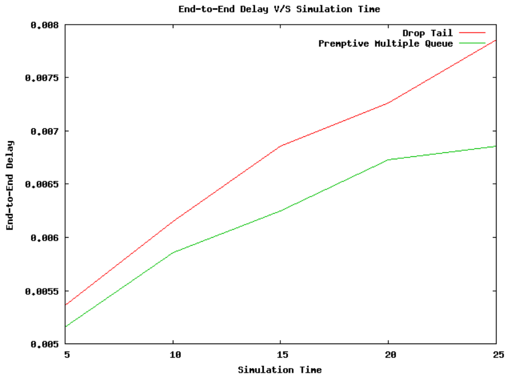

Fig. 12. End-to-End delay of packets in AQM mechanisms

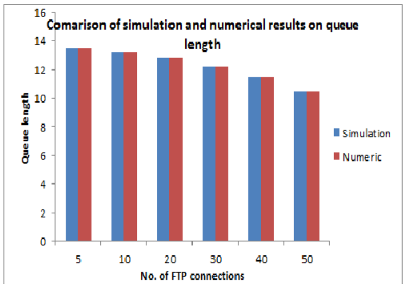

Fig. 13. Comparison of mean-q-length in analytical and simulation mechanisms

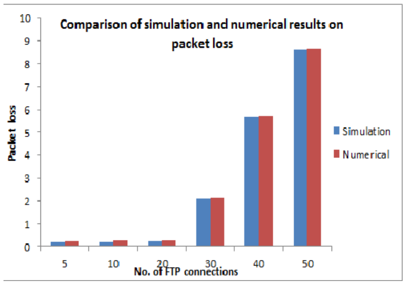

Fig. 14. Comparison of packet loss in analytical and simulation mechanisms

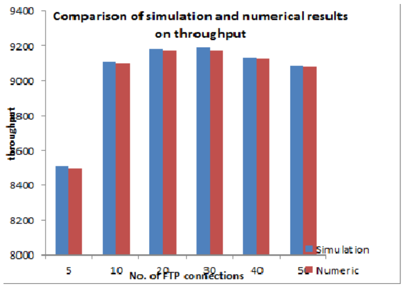

Fig. 15. Comparison of throughput in analytical and simulation mechanisms