Performance Evaluation of Adaptive and Static Routing Algorithms and Contention Resolution Techniques in LEO Satellite Constellations

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***Abstract*- This paper evaluates static, adaptive, and semi-adaptive routing algorithms and packet contention resolution techniques in a low earth orbit (LEO) satellite constellation in terms of throughput and fairness for both uniform and bursty traffic models. In order to make such an evaluation, it is crucial to find out how thoughtput and packet drop ratio is affected by various parameters, i.e. implementation of buffers at each satellite, number of transmitters per satellite, instantenous network traffic load, type of the traffic (bursty vs uniform), and the burst size for non-uniform traffic. Simulations are made to investigate the effects of these parameters. Moreover, simulation results are plotted to better illustrate these effects on throughput and fairness of packet contention resolutions schemes and routing algorithms. The contention resolution schemes emloyed during simulations are *Shortest Hop Win (SHW), Oldest Packet Win (OPW)and Random Packet Win (RPW)* proposed in [1]. The routing algorithms used are *static routing and adaptive routing* described in [2] *and semi-adaptive routing* developed during the simulations.**

I. INTRODUCTION

In order to achieve high throughput for a satellite network, contentions caused by random nature of packet traffic should be resolved. In this paper*, we focus on the contention problem of a low earth orbit (LEO) satellite network for inter-satellite communication. We modeled the satellite constellation as NxN mesh topology which is a 2-D N-ary hypercube with four neighbors per node. Contention for transmission occurs inevitably, when multiple packets arrive at each satellite.

In the literature, contention resolution techniques have been proposed for such mesh networks. One of the techniques is deflection routing that is proposed and studied analytically in [3]. Ref. [4] analyzes the efficiency of greedy routing techniques in hypercube networks. Ref. [5] proposes different routing techniques and evaluates throughput for those techniques in the case of buffered and no buffer satellite networks. In [1], proposed contention resolution techniques depend on the decision of which packet to drop in the case of contention. They propose mainly three scheduling schemes: random packet win (RPW), oldest packet win (OPW), and shortest hop win (SHW). We consider all these techniques in this paper and compare them in terms of throughput, as well as fairness.

Initially we assume that each node has a single transmitter and four receivers, i.e. a satellite (node) can only transmit a single packet in a time slot, although it can receive up to four packets simultaneously. Furthermore, we investigate the effect of increasing number of transmitters of each node. If and only if the number of transmitters is greater than one, adaptive routing becomes applicable. Adaptive routing has many benefits [2]. It improves the blocking probability by using alternate routes when congestion occurs. We employed adaptive and semi-adaptive routing schemes, as well as non-adaptive (static) routing scheme, and compare their performance by simulations for different network parameters.

II. CONTENTION RESOLUTION SCHEMES

In this section we discuss several scheduling schemes for contention resolution described in [1]. These scheduling techniques rely on giving different priorities to packets, depending on their characteristics.

In *RPW*, among more than one continuing packets, one is chosen randomly and transmitted and others are located to buffer if there is available space. If available space is less than the number of buffer candidates, RPW randomly selects among them to store into buffer. If there is no continuing packet, the packet in the head of the buffer is transmitted. If buffer is also empty, a new packet is transmitted (if there is one). *OPW* is same as RPW, except that it selects the packet that has traveled more hops among all continuing packets. *SHW* is also same as RPW, except that it selects the packet with the shortest hop distance to its destination node.

OPW is expected to perform better than RPW in terms of throughput, since it reduces the resource waste by prioritizing

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packets that have already traveled a long way. SHW scheme is expected to give best throughput results, since it reduces the load in the system by getting packets out of the system as soon as possible. However, it gives poor fairness results since packets with shorter routes are prioritized for transmission over the packets that should travel more hops to their destination. OPW favors long paths on shorter paths and thus it gives better fairness results. RPW performs better than SHW in terms of fairness, but it is not as fair as OPW.

The above descriptions are valid when each node owns a single transmitter. When each node owns more than one transmitter, continuing packets are still prioritized over others. If we denote the number of continuing packets by c and the number of transmitters by T, then $c < T$ implies that node can transmit $T - c$ more packets. In this case first buffer is checked, and $T - c$ packets waiting at the head of the buffer are selected for transmission. If the outgoing link of the selected packet is unavailable, then packet is placed back to the buffer. Finally, packets inside the buffer are sorted with respect to their original arrival times to the buffer. If the number of transmitted packets is still less than $T - c$ and if there exists a newly generated packet, node transmits this packet. In [1] it is shown that maximum throughput for one transmitter case is 0.182 for 11x11 mesh. When number of transmitters is increased to two, maximum number of transmissions per unit time doubles, and therefore maximum throughput is 0.364. Similarly for three and four transmitter case, it is 0.546 and 0.728 respectively.

III. Adaptive Routing

In **non-adaptive (static)** routing, the choice of the route between a source destination pair is computed in advance, offline and downloaded to the routers when the network is booted. In this scheme, a satellite node can only transmit a new packet when the predefined outgoing link is idle at that moment. Otherwise new packet would be dropped even if other links are available. Utilization of the network resources could be increased by using an alternative route in such a case. This scheme is known as **adaptive routing**. However, it should be noted that in order to make adaptive routing applicable, some conditions should be satisfied. Firstly, the alternative route should differentiate from the original one from the beginning of the route. Otherwise alternative route would also be impossible to use when the outgoing link for the original route is unavailable. Furthermore, number of transmitters should be more than one. If there is only one transmitter, packet generation is already impossible regardless of the availability of the links. If these conditions are satisfied it is expected that adaptive routing outperform static routing. The simulation results also show this. Contribution of adaptive routing becomes more evident especially when number of transmitters is four.

In static routing, most of the packet drops occur in packet generation stage and a generated packet would most probably reach to its destination. However, in the case of adaptive routing, fewer packets are prevented from entering the network at the source and number of drops for the packets that have already entered the network increases. This is a disadvantage of adaptive routing as it puts an increased burden on higher layer protocols to recover the dropped packets. In order to reduce the effect of this disadvantage, we propose **semi-adaptive** routing scheme.

Semi-adaptive routing acts as adaptive routing when there exits more than one shortest path for a given source destination pair. When there is only one shortest path between a source-destination pair, semi-adaptive routing acts as static routing. Simulation results show that semi-adaptive routing does not perform better than adaptive routing in terms of throughput, but it is advantageous because it reduces number of retransmissions.

Adaptive and semi-adaptive routing schemes are employed in simulations only when each satellite in the network owns multiple transmitters. According to simulation results, for both uniform and bursty traffic models, throughput for adaptive routing outperforms slightly. Packet drop ratio is less for adaptive routing compared to the other two routing schemes as long as the hops a packet should travel to its destination is smaller than half of the maximum shortest hop length.

IV. Simulations

Simulation Setup

In the simulation environment, a LEO satellite network is modeled as an NxN mesh i.e. two dimensional N-ary hypercube. Simulations are performed for an 11x11 mesh and each node corresponds to a satellite. The number of receivers owned by each node is constant, and equal to four, while the number of transmitters varies between one and four during simulations.

The nodes operate synchronously as in [1] and time axis is divided into slots. During each time slot, a new packet is generated independently at each node locally with a probability of p_0. At the end of a time slot, there are up to four continuing packets that are sent by the neighboring nodes, there might be a new packet generated locally with probability p_0, and also there might be packets waiting inside the buffer. Since transmission scheduling schemes SHW, OPW and RPW [1] are used, routers at each node gives more priority to continuing packets than the packets waiting inside the buffer (if nodes have buffers).

Simulations are performed for both uniform and bursty traffic. When traffic is uniform, at each time slot a new packet arrives to a node according to Bernoulli process with a rate of p_0. On the other hand, to burst size obeys a uniform distribution in the interval between 1 and maximum burst size, r. During the simulations, maximum burst size is taken to be 10. In order to observe how throughput is affected by maximum burst size for adaptive, semi-adaptive and non-adaptive routing schemes, maximum burst size is varied between 1 and 40. During these simulation series, the number of transmitters per node is taken to be two.

Simulation Results for Uniform Traffic

Uniform traffic simulations are performed for both buffered and no buffer cases. The simulation results show that among the transmission scheduling schemes SHW gives best throughput results for no buffer case. However, fairness results are poor for all transmission schemes. SHW gives the highest packet drop ratios since the number of hops that packets have to travel in order to reach their destinations increase. Fairness results in terms of packet drop ratio are improved, when each node owns a buffer of fixed size. However, in general, SHW, OPW and RPW exhibit similar throughput performance under uniform traffic in case of no buffers at satellites.

A. Throughput and Fairness Results for No Buffer Case

According to the results of the simulations performed to compare SHW, OPW and RPW, best throughput results are obtained for SHW. As it is shown in Fig. 1, our results are consistent with the corresponding results in [1]. In order to see fairness results in terms of packet drop ratio, we performed simulations for three different traffic loads which are $p_0 = 0.1$, $p_0 = 0.5$ and $p_0 = 0.9$ respectively. The results of these simulations are presented in Fig. 2, Fig. 3. and Fig. 4.

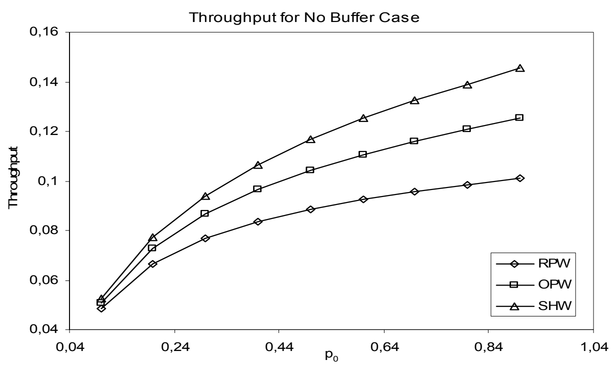

Figure 1. Throughput of SHW, OPW, RPW for no buffer

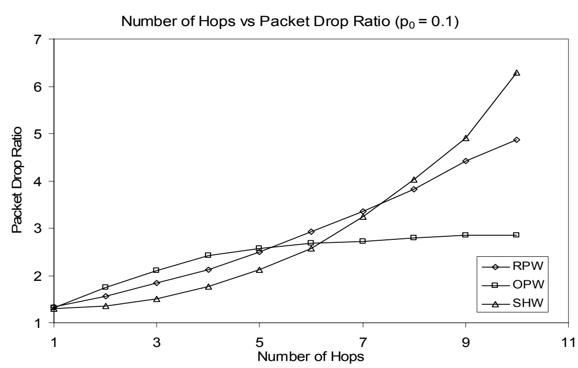

Figure 2. Fairness of SHW, OPW, RPW for no buffer p_0=0.1

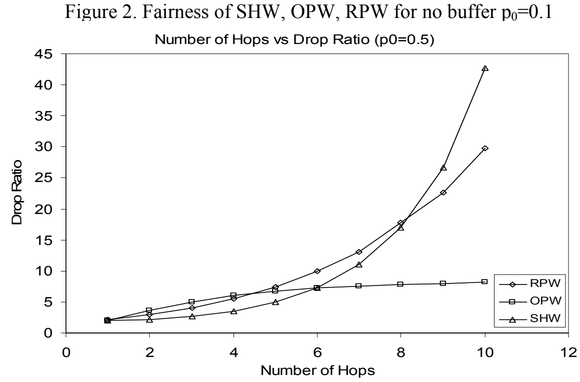

Figure 3. Fairness of SHW, OPW, RPW for no buffer p_0=0.5

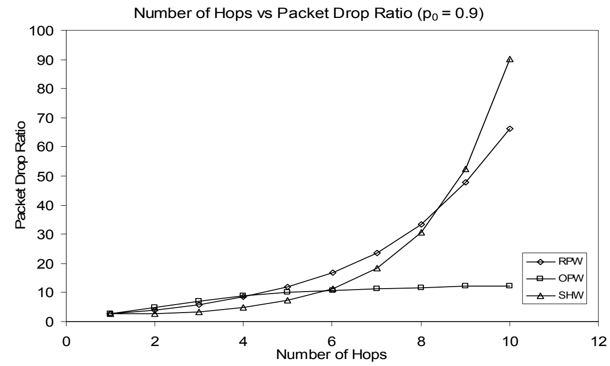

Figure 4. Fairness of SHW, OPW, RPW for no buffer p_0=0.9

Since continuing packets are more likely to have a shorter distance to their destination and SHW gives priority to packets that are about to exit the network, throughput outperforms when SHW is employed rather than OPW or RPW. On the other hand OPW performs better than RPW, since it minimizes the wasted work done for a continuing packet by giving priority to the packet that has traveled the longest distance as presented in Fig. 1.

Fig. 2 shows the results of the simulations for low traffic load performed to compare SHW, OPW and RPW in terms of packet drop ratio as the number of hops a packet travels in order to reach its destination increases. While number of hops is smaller than 6 which is greater than half of the maximum shortest path (maximum shortest path is evaluated as *N-1*, thus with *N=11, (N-1)/2 =5*), packet drop ratio is the least for SHW. This is because SHW gives priority to packets that are about to exit the network. The worst performance is given by OPW, since it gives priority to packets that have traveled the longest distance and thus most of the packets with small number of hops to their destination are dropped. When number of hops becomes greater than half of the maximum shortest path, SHW exhibits the poorest fairness, while OPW outperforms. The behavior is more evident when traffic load is medium and high as it is shown by Fig. 3 and Fig. 4 respectively. In addition, we observe significant increase in packet drop ratio as traffic load increases.

In order to see the change in throughput with respect to the increase in the number of transmitters, we performed another simulation whose result is given in Fig. 5. As the number of transmitters increases from 1 to 2, a sharp increase in throughput is observed. However, as we continue to increase the number of transmitters to 3 and 4 respectively increase in throughput becomes smoother. This is due to the fact that packets mostly need to be routed along first and second transmitters. As the number of transmitters increases, more packets are transmitted (generated packet is not dropped easily), this allows the node to send more packets into network. Network becomes congested; throughput of the network tends to reach a steady state around the total capacity.

Comparison of throughput between adaptive, semi-adaptive and static routing is given in Fig. 6. As it can be seen from the figure, adaptive routing slightly surpasses the static routing scheme for the case when number of transmitters is 2.

This is because when number of transmitters is 2, most of the packet drops occur because of the scarcity of transmitters, rather than unavailability of routes for newly generated packets. As it can be seen from Fig. 5, performance difference between adaptive and static schemes increases as the number of transmitters increase. This is because when number of transmitters increase, transmitter scarcity is no more a problem for newly generated packets and therefore alternate paths are better utilized. The idea could also be observed from Fig. 7 which illustrates throughput with respect to the increase in the load for number of transmitters being four.

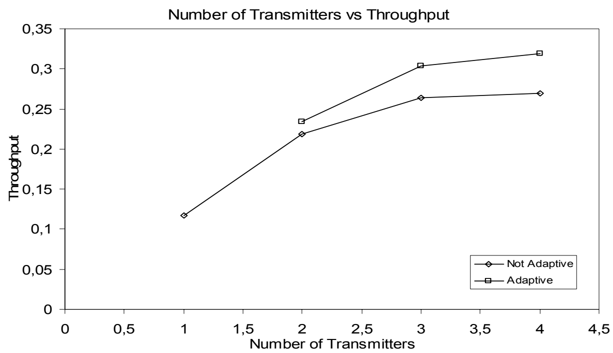

Figure 5. Throughput vs. number of transmitters for no buffer

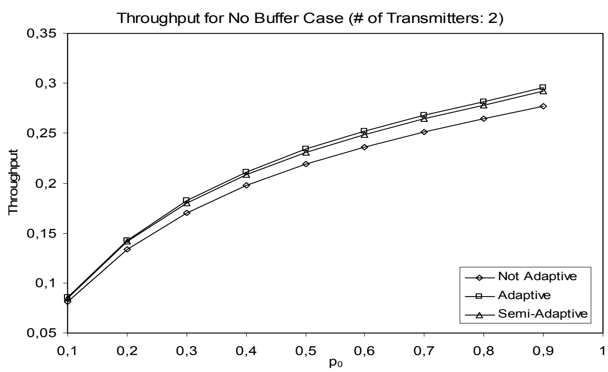

Figure 6. Throughput of routing schemes for no buffer T=2

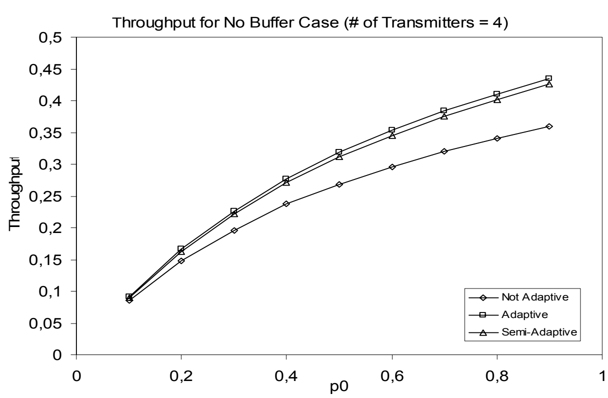

Figure 7. Throughput of routing schemes for no buffer T=4

B. *Throughput and Fairness Results for Fixed Buffer Case*

When simulations are performed for the case when each node contains a buffer with a fixed size of 4, we obtain better throughput results compared to no buffer case. Fig. 8 shows throughput comparison results for SHW transmission scheduling scheme. This is an expected result since packets are usually kept waiting at buffers instead of immediately being dropped as it is inevitably done in no buffer case. Thus, throughput increases as more packets arrives their destination (packets are put into buffers instead of just being dropped in network). On the other hand, unlike no buffer case, throughput results for SHW, OPW and RPW are similar (see Fig. 9). This is because most of the packet drops occur at the source node. Since the number of dropped packets decrease due to the existence of buffers at each node, a significant improvement in fairness in terms of packet drop ratio occurs.

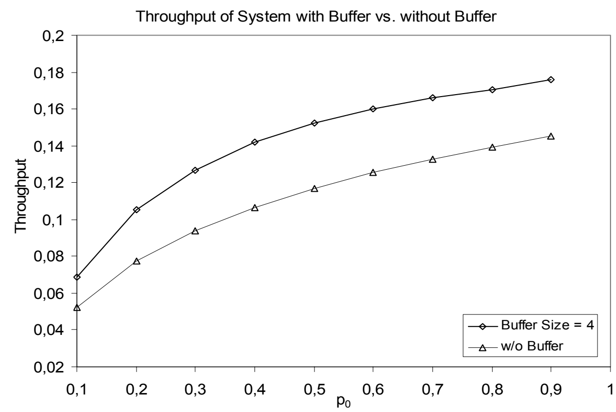

Figure 8. SHW Throughput without buffer vs. with buffer (size=4)

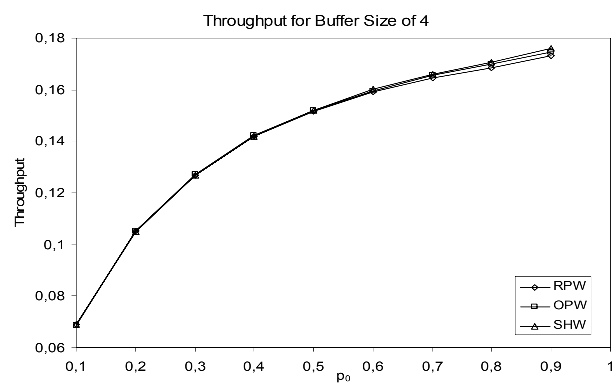

Figure 9. Throughput of SHW, OPW, RPW with buffer (size=4)

As traffic load increases, drop ratio for the packets that have to travel more hops to reach to their destination increases with respect to others and fairness decreases. In such cases most unfair conditions are observed in SHW. OPW becomes fairest contention resolution scheme as it can be seen from Fig.10, Fig. 11 and Fig 12. This behavior is similar to the one we observed for no buffer case. Although there exists a significant improvement in terms of fairness compared to the no buffer system, the packet drop rates increases as the network becomes congested as it is the case for no buffer case (See Fig. 10, Fig. 11, and Fig. 12).

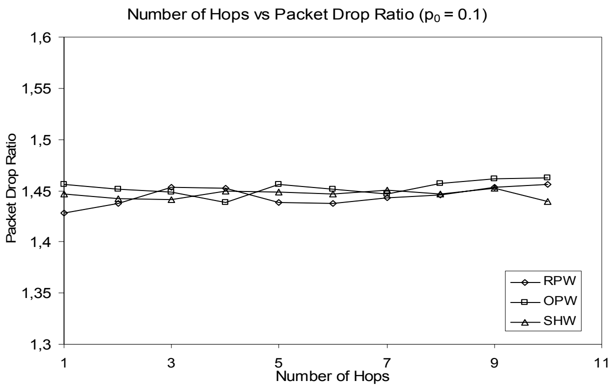

Figure 10. Fairness of SHW, OPW, RPW with buffer size=4, p_0=0.1

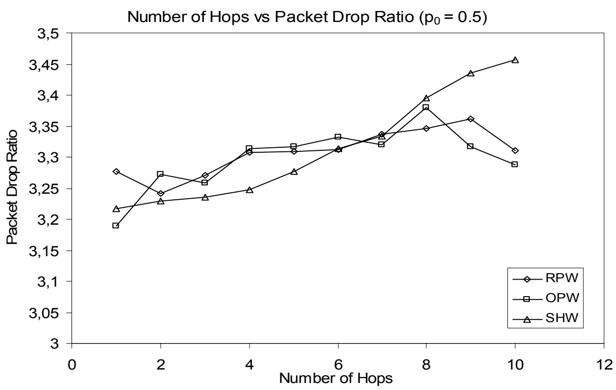

Figure 11. Fairness of SHW, OPW, RPW with buffer size=4, p_0=0.5

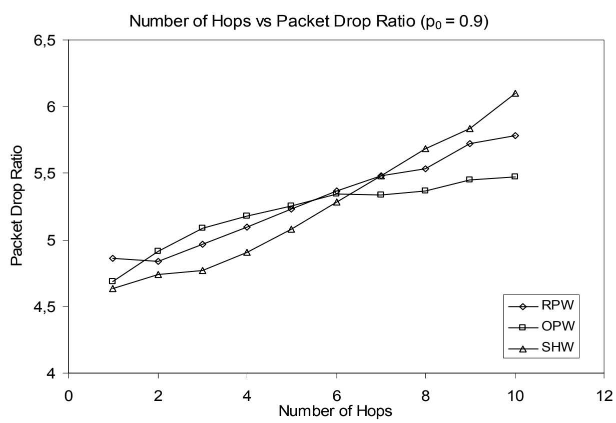

Figure 12. Fairness of SHW, OPW, RPW with buffer size=4, p_0=0.9

In order to observe the buffers impact on the routing schemes described above (static, adaptive and semi-adaptive), we make simulations with buffer size 4, where each node has two transmitters. The results are illustrated on Fig. 13. We see that all routing schemes perform similarly, and there is a slight increase in terms of throughput than the no buffer case. Throughput difference between three routing schemes decreases and their throughput vs. p_0 plot approaches each other.

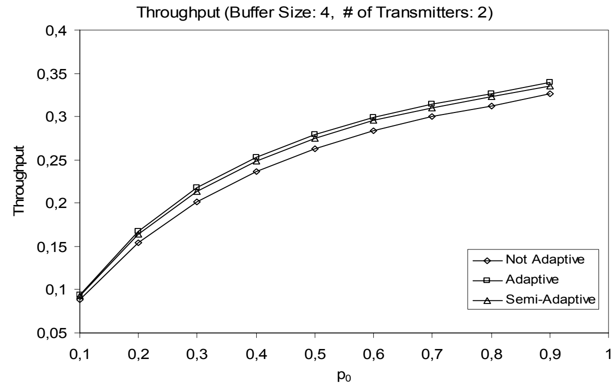

Figure 13. Throughput of routing schemes with buffer size=4, T=2

Simulation Results for Bursty Traffic

During the simulations for bursty traffic, burst size is taken to be 10, as a fixed value. That is, once a node produces a packet with probability p_0 in one time-slot, it keeps producing a packet per time-slot for the succeeding nine time-slots. Simulations are performed for the cases when number of transmitters per node is one and two respectively. Since it is obvious that no buffer case will give worse results compared to buffered case, buffer size of each node is set to four. Apart from the results of uniform traffic, throughput results for SHW, OPW and RPW are no longer similar to each other (see Fig. 9 and Fig. 14 respectively). Compared to OPW and RPW, SHW gives much better throughput results, since existence of buffer can no longer compensate packet drops due to bursty traffic. Thus, giving preference to packets that are about to leave the network causes an increase in throughput (See Fig. 14).

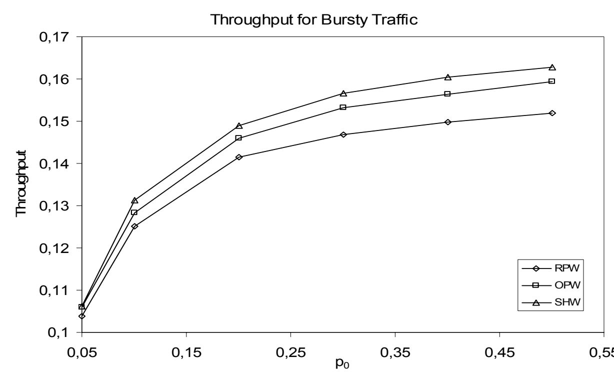

Figure 14. Throughput of SHW, OPW, RPW for bursty traffic with buffer size=4, T=1, burst size=10

As it can be seen in Fig. 14 and Fig. 16, there is a decrease in throughput compared to the case when uniform traffic is employed for corresponding traffic loads. This is an expected result, since as traffic becomes bursty it is much more likely for the packets to be dropped. The difference between throughput results for adaptive routing and the other two routing schemes becomes larger under bursty traffic as compared to uniform traffic case (See Fig. 13 and Fig. 15). However, under uniform traffic throughput results for adaptive, semi-adaptive and non-adaptive routing were much closer to each other. (See Fig. 13)

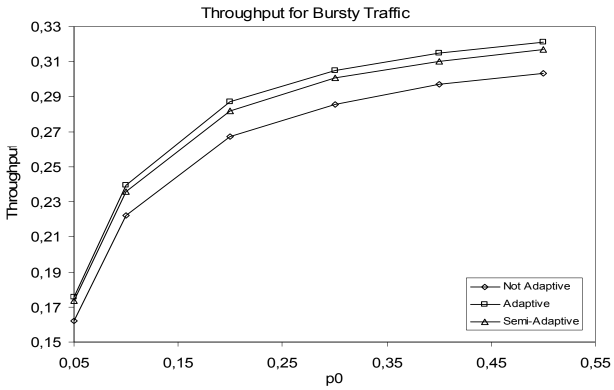

Figure 15. Throughput of routing schemas for bursty traffic with buffer size=4, T=2, burst size=10

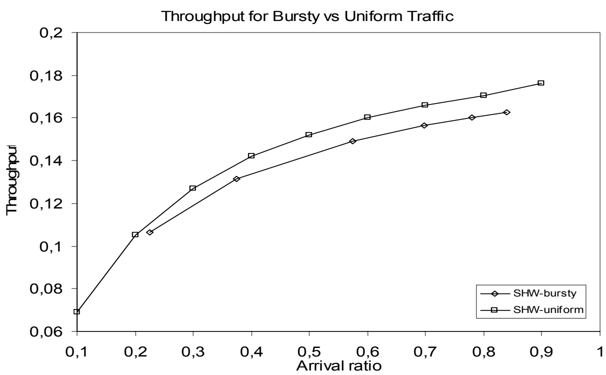

Figure 16. SHW Throughput for bursty vs. uniform traffic with buffer size=4, T=1, burst size=10 for bursty traffic

As maximum burst size increases from 1 to 10, we observe a sharp increase in throughput for adaptive, semi-adaptive and non-adaptive routing schemes. Since maximum burst size is low, transmitter has opportunity to transmit more continuing packets and thus preventing high contention. Since the number of packets requiring adaptive and semi-adaptive routing to be transmitted decreases, there is a slight difference between throughput values of these routing schemes when maximum burst size is small. When maximum burst size is greater than 10, difference between throughput results of the routing schemes increases slightly (see Fig. 17). This is due to the fact that each source-destination pair owns a single alternate node, thus contention shall still occur as packets will require to be transmitted along coinciding alternate paths.

V. Conclusion

This paper focuses on the transmission scheduling schemes and the routing algorithms in LEO satellite networks under different type of traffic and various transmitter receiver combinations in each satellite. In order to evaluate network performance of these routing and packet scheduling schemes, simulations are done, whose plots illustrate throughput and fairness measures. Under uniform traffic, Shortest Hop Win (SHW), Oldest Packet Win (OPW), and Random Packet Win (RPW) are compared for both no buffer and buffered systems. SHW gives better throughput results when the satellites do not have buffers. Interestingly, all transmission scheduling schemes behaves very similarly when buffers come into play. However we clearly observe that buffered satellite network throughput surpasses the satellite without buffer system throughput.

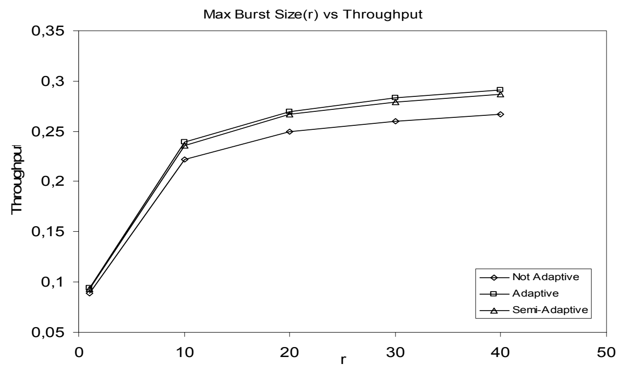

Figure 17. Throughput of routing schemas vs. varying burst size, buffer size=4, T=2

Throughput values become larger as the number of transmitters increases at each satellite until network reaches a steady state around the network capacity. As for the fairness measure, we make use of the packet drop ratio for packets that should travel different hop distances. Despite its high performance, SHW is worst in the case of fairness. OPW is observed to be most fair contention resolution technique.

When we look at the throughput of network under adaptive, semi-adaptive and static routing, we see that routing strategy has minor effects on throughput when number of transmitters is two. As number of transmitters is increased, adaptive routing schemes outperform static routing schemes with a considerable throughput difference.

Apart from the findings summarized in above paragraphs, where the traffic is uniform, we look at throughput values for the bursty type traffic. When a satellite undergoes bursty traffic, system becomes more fragile, and difference among various packet transmission schemes and routing types becomes more apparent.

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