Tailoring ELB for Multi-layered Satellite Networks

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***Abstract*— Over the years, the concept of multi-layered satellite networks has indeed become popular. Researchers have developed a wide variety of techniques related to these particular networks. However, users of satellite networks will exhibit high variances due to their diverse geographical distributions. This causes traffic concentrations at particular satellites to increase drastically resulting in high packet drop rates and severe degradation of Quality of Service (QoS). The Explicit Load Balancing (ELB) scheme was developed to address these issues in Low Earth Orbit (LEO) satellite networks. In ELB, each satellite monitors its own queue and exchanges traffic-load information among its neighboring satellites. The satellites that experience heavy traffic attempt to alleviate the traffic load by redirecting a portion of the traffic via alternative paths. To cope with network congestion (over a single layer) and for better traffic distribution, multi layer satellites were proposed. In this paper, we propose an efficient traffic distribution scheme for multi-layered satellite networks based on ELB in which we extend the range for exchanging the traffic-load information for achieving further reductions in packet drop rates. In addition, we present an enhanced technique for computing the detouring ratio more efficiently. We demonstrate via simulations that the proposed approach effectively improves the performance of ELB over multi-layered satellite networks.**

I. Introduction

Next generation multi-hop satellite IP networks are expected to play an integral role in the construction of a large scale wireless network infrastructure to mitigate the worldwide digital divide and to also provide ubiquitous wireless broadband services. With this end, multi-layered satellite networks, consisting of different satellite constellations, came into use for enhancing the communications quality on a Global scale [1]. These multi-layered satellite networks are, however, not without their shortcomings. Unbalanced traffic load distribution tends to occur in these satellite networks owing to the uneven distributions of users all over the world. In addition to this, the explosive growth in the use of high-speed Internet is making this problem more significant. To overcome these complications, it is an imperative that we should devise new and efficient routing techniques for multi-layered satellite networks.

In one of our earlier works, we proposed the Explicit Load Balancing (ELB) scheme for mitigating traffic concentrations in Low Earth Orbit (LEO) satellite networks [2,3,4]. In the ELB scheme, each satellite periodically monitors its own queue length in order to foresee an imminent congestion. If the ratio of the current queue occupancy to the total queue size of a satellite exceeds a pre-computed threshold, the satellite is considered to be in a congestion state. The congested satellite then requests its immediate neighboring satellites to detour a portion of its traffic. Upon receiving such request messages, the satellites adjacent to the overloaded satellite start redirecting a portion of traffic via alternative paths. In this fashion, ELB mitigates the traffic load concentration at the busy satellite. Thus, ELB eventually reduces packet drop rates and also enhances the overall Quality of Service (QoS).

In this paper, we identify the problems in the original ELB scheme that have arisen due to the shifts in satellite network architectures and uneven distributions of users on the ground. We then focus on tailoring the ELB scheme to the case of multi-layered satellite networks. ELB is improved in terms of i) The range over which signaling messages are exchanged amongst the busy satellite and its neighbors, ii) the operations to update routing tables at the satellites, and iii) the manner in which the detouring ratio for the redirected traffic is computed. In multi-layered satellite networks, congestions are more likely to occur over densely-populated regions such as urban areas. For better congestion control, the traffic over populated areas must be reduced regardless of the underlying satellite layers.

The remainder of this paper is organized as follows. Section II discusses some related works and briefly describes the original ELB scheme. We introduce our envisioned enhancements to ELB in Section III. The performance of the proposed scheme is evaluated in Section IV. Finally, we present concluding remarks in Section V.

II. Related Work

A. Routing Techniques for Multi-layered Satellite Networks

In recent times, many researchers have addressed the need for efficient routing techniques over multi-layered satellite networks. Most of these routing techniques are based on Dijkstra's shortest path algorithm. For instance, Hu *et al.* [5] specifically designed a routing method for long-distance sessions over MEO satellites. In this approach, mobile terminals on the ground connect to LEO satellites, which bridge the ground with the satellites at the MEO level. Thus, the MEO satellite network is used as the core network. Mobile terminals can save their electrical power and efficiently use their communication resources. In this work, Hu *et al.* proposed a novel routing algorithm called Maximum Holding Access Protocol (MHAP) for the access networks, and also investigated the performances of two other routing schemes, namely Minimum Transmission Delay Routing (MTDR) and Minimum Transmission Time Jitter Routing (MTJR), which were employed for routing in the MEO core network. In [6], Bayhan *et al.* proposed a routing technique called Adaptive Routing Protocol for QoS (ARPQ) for forwarding delay-sensitive packets rapidly over multi-layered satellite networks consisting of MEO and LEO satellite constellations. Based on an end-to-end threshold, these delay sensitive flows are classified into short-distance and long-distance sessions. Packets that belong to the long-distance sessions are forwarded via the MEO satellite layer while the other packets are transmitted via only LEO satellites. In this approach, satellites with the least queue utilization are employed for transmitting the data packets for achieving traffic load balancing.

Akyilidiz *et al.* [7] discussed a routing management method for satellite networks with three layers consisting of geo-stationary, MEO, and LEO satellites, respectively. In multi-layer satellite networks, the signaling costs increase with the number of satellite constellations. Akyilidiz *et al.* addressed this issue and devised a novel routing method called Multi-layered Satellite Routing (MLSR) algorithm. The key idea behind the MLSR approach consists in an efficient use of the hierarchical structure of the network topology, whereby the satellites in the upper level gather information related to routing (e.g., queueing delays) from the satellites at the lower levels. The upper level satellites then broadcast these information to other satellites within their visibility ranges. The satellites employ these information in making their routing decisions.

B. Explicit Load Balancing for LEO Satellite Networks

In our previous works [2,3], we envisaged the Explicit Load Balancing (ELB) mechanism to deal with congestion problems arising at the satellites in a LEO satellite network. In ELB, each satellite monitors its own buffer to detect an imminent congestion. Two thresholds, α and β, are defined for the ratio of the current queue occupancy to the total buffer size, Q_r. Based on the value of Q_r, each satellite functions in one of the three modes, namely free, fairly busy, and busy states. A satellite that is about to switch to a busy state interprets the event as an indication of an imminent congestion. It then sends a Busy State Advertisement (BSA) message to its neighboring satellites. Each BSA contains the desired Traffic Reduction Ratio (TRR). In response to the received BSA message, the neighboring satellites detour a portion of packets, based on the requested TRR value, to alternative paths. By performing such a traffic redirection, the traffic load at the satellite, which is in a busy state, is reduced, and the otherwise-associated congestion may be alleviated.

ELB was further improved in [4] by extending the range of BSA-exchanges which resulted in better performances in terms of reduced packet drops and more effective traffic distributions. In this enhanced version of ELB, a satellite transiting to a busy state sends BSAs not only to its immediate neighbors, but also to a wider range of satellites, k-hops distant, where k is a constant. The Traffic Reduction Ration (TRR) at each i^{th} hop-neighboring satellite (i.e., TRR_i) follows a Gaussian distribution, where $(1 \leq i \leq k)$. By extending the range in this fashion, packets originally destined for the satellite in the busy state are detoured along further hops in the network. This approach thus prevents a satellite in busy mode to avoid heavy concentration of traffic.

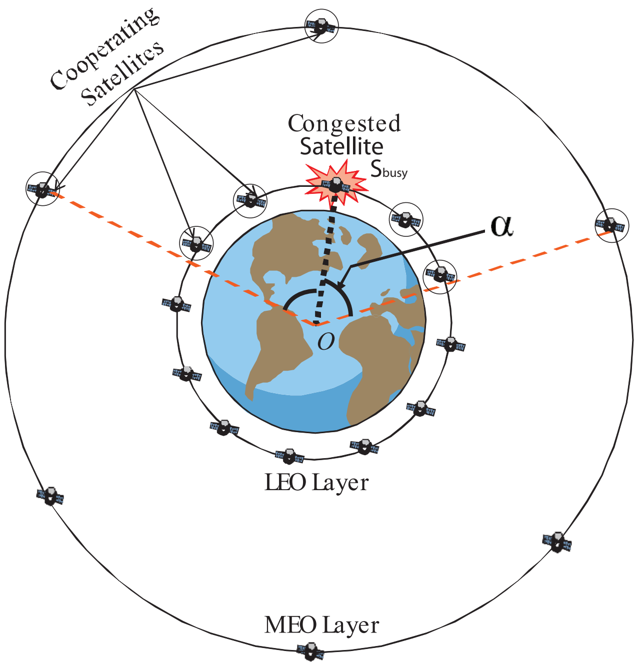

Fig. 1. Range of BSAs exchange based on the angle α.

III. Proposed Method: ELB for Multi-Layered Satellite Networks

The contemporary routing strategies fail to effectively prevent local congestions, which lead to increased packet drops, and degraded throughput and QoS mainly in case of satellite networks given their long propagation delays. Although applying queueing delays as link costs may lead to a certain level of traffic load balancing, a prompt reaction to an imminent congestion is still not quite possible in these existing routing schemes. Therefore, it is essential that we anticipate such a scenario *a priori* and deal with it appropriately. With this view in mind, we re-design ELB for multi-layered satellite networks in this paper. The main contributions in this paper are three fold. First, we intend to avoid congestion at satellites as locally as possible. The range of exchanging BSAs and the link costs are arranged over each satellite layers. Second, we ensure that the current satellite network conditions are reflected in the routing decisions. To this end, routing tables are adequately updated. Finally, we present an enhanced method for computing the detouring ratio in order to cope with high fluctuations in traffic. In the remainder of this section, we describe these contributions in details.

A. Range of exchanging BSAs

A satellite in busy state, S_{busy}, sends Busy State Advertisements (BSAs) to its surrounding satellites. A BSA message contains the ID of S_{busy} and also the Traffic Reduction Ratio (TRR) requested by S_{busy}. When a satellite receives a BSA message from S_{busy}, it switches to the detouring mode and forwards a portion of traffic to alternative links that do not involve the busy satellite. We consider the angle, α, shown in Fig. 1, to define the maximum range, in which S_{busy} may exchange BSAs with other satellites. In other words, the angle between the vertical line of a satellite (to the center of the earth) that is to receive a BSA message and that of S_{busy} should be less than or equal to α. In order to alleviate traffic concentrations at S_{busy}, we thus employ the satellites over a wide area around S_{busy}, defined by (2α), to detour the traffic originally destined for S_{busy}. The reason behind this choice is the fact that such congestions occur due to variances in the geographical distribution of users. Therefore, traffic loads above a wide area of populated regions should be controlled at all the layers of the considered satellites networks. The computation method of TRR at each neighboring satellite is presented in subsection C. Each satellite, in our approach, maintains a table containing information regarding the states of its neighboring satellites (in both LEO and MEO layers), which are within its range of BSAs exchange. In addition, every satellite holds two routing tables. The first routing table is used for handling normal packets, i.e., non-detoured packets, using existing routing schemes. In order to construct this routing table, link costs are assigned to all Inter-satellite Links (ISLs) based on propagation delays and queueing delays. Discussion on how these link costs are updated and notified to satellites are presented in the next subsection. The second routing table is constructed for handling detoured packets based on the detouring link costs specific to the underlying routing algorithm used. The detouring link cost from a satellite S_i to an adjacent satellite S_j is denoted by $L_{d(i,j)}$, which is computed as follows.

1) If none of the neighboring satellites within the BSAs exchange range of S_{busy} (S_i in this particular case) are not in busy state, $L_{d(i,j)}$ is simply set to the normal link cost from satellite S_i to satellite S_j ($L_{d(i,j)} = L_{n(i,j)}$).
2) If satellite S_j is in busy state, $L_{d(i,j)}$ is set to a large value (e.g., ∞).
3) If satellite S_j is in free state and if another satellite S_l, which is within S_i's range of BSAs exchange and is accessible via S_j, is in a busy state, then we compute $L_{d(i,j)}$ as follows:

$$L_{d(i,j)} = L_{n(i,j)} \cdot (1 + f(A_{i,l})) \tag{1}$$

where $A_{i,l}$ denotes the angle between the vertical lines of S_i and S_l. $f(A_{i,l})$ is a decreasing utility function; the closer S_i to S_l, the higher the cost. In this paper, we consider the following Gaussian function as the utility function:

$$f(A_{i,l}) = \beta \cdot \exp\left(-\frac{1}{2\sigma^2} \cdot \left(\frac{A_{i,l}}{\alpha}\right)^2\right) \tag{2}$$

where α and β are real constants.

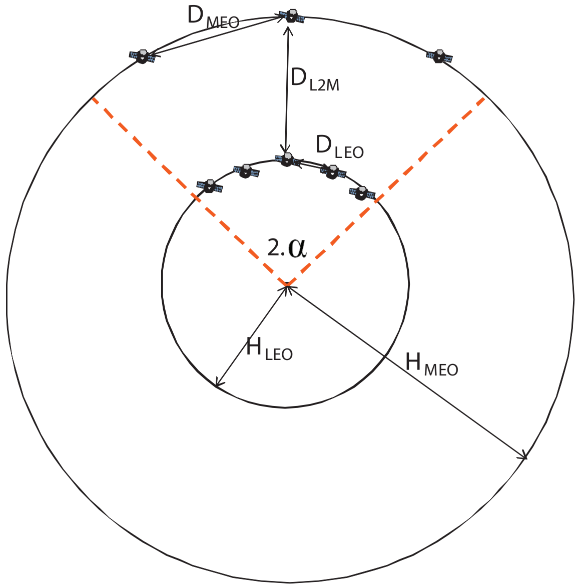

Fig. 2. A simplified model of a multi-layer LEO/MEO satellites network.

B. Link Cost Update

First of all, we note that as in the original version of ELB, a satellite starts broadcasting BSA messages to its neighboring satellites immediately after the occurrence of a state transition (i.e., when the satellite switches from fairly busy to busy state). For this purpose, every satellite is assumed to monitor the length of its own queue every δ time, which is set to $20ms$ throughout this paper.

As mentioned earlier, queueing delays are used for computing the link costs for routing. For an efficient routing operation, the dynamic changes in the traffic load and the resultant queueing delays need to be regularly reflected in the link costs. In addition, these link costs should be notified to all satellites as frequently as possible. However, the communication delays increase proportionally along with the number of traversed satellites. As a result, a high frequency of link cost notifications over the entire constellation leads to a high number of signaling messages. On the other hand, a low frequency of link cost notifications may indeed lead to erroneous routing decisions. Therefore, depending on the considered satellite network, one needs to determine how often all the satellites should be informed about the up-to-date link cost values.

In this paper, two types of routing table updates are envisioned, namely "locally distributed" and "globally centralized" updates. The latter is based upon the central routing table calculation mechanism delineated in [7]. In this mechanism, LEO satellites send their delay measurement reports to their corresponding upper-layer MEO satellites. Upon receiving these reports, the upper layer satellites exchange the same among themselves, calculate individual routing tables for each LEO satellite in their respective coverage areas, and finally send these routing tables to the corresponding LEO satellites via minimum hop paths.

Given the size of the constellation, these global and central routing table calculation methods, alone, are not sufficient to reflect the current conditions of the constellation or its on-going dynamics. In order to effectively avoid congestion at a local level, we adopt an approach based on computations of locally distributed routing tables. As demonstrated in the satellite network depicted in Fig. 2, LEO satellites notify their corresponding MEO satellites of their average queueing delays every δ_{L2M} period of time, similar in spirit to the "globally centralized" approach.

$$\delta_{L2M} = \gamma \cdot D_{L2M} \tag{3}$$

where D_{L2M} denotes the inter-layer ISL delay. γ indicates how much overhead in terms of signaling messages the system is willing to tolerate. For simplicity, γ is set to one throughout the remainder of this paper. In the MEO constellation, each MEO satellite notifies its neighboring satellites within its BSA exchange range of its average queueing delay every δ_{MEO} period of time.

$$\delta_{MEO} = \left\lfloor \frac{H_{MEO} \cdot \alpha}{D^{OD}_{MEO}} \right\rfloor \cdot ISL_{MEO} \tag{4}$$

where H_{MEO}, D^{OD}_{MEO}, and ISL_{MEO} denote the altitudes of the MEO satellites, the orbital distance between two adjacent MEO satellites, and the ISL delay of the MEO constellation, respectively. The first term on the right hand side of Eq. 4 indicates the maximum number of MEO satellites along the radius of the BSA exchange range (as illustrated in Fig. 2). Similarly, a LEO satellite notifies other LEO satellites (within its BSA exchange range) of its average queueing delay every δ_{LEO} time, which is calculated as follows:

$$\delta_{LEO} = \min \left((\gamma + 1) \cdot D_{L2M}, \left\lfloor \frac{H_{LEO} \cdot \alpha}{D^{OD}_{LEO}} \right\rfloor \cdot ISL_{LEO} \right) \tag{5}$$

where H_{LEO}, D^{OD}_{LEO}, and ISL_{LEO} denote the altitudes of the LEO satellites, the orbital distance between two adjacent LEO satellites, and the ISL delay of the LEO constellation, respectively. In this equation, the first element of the "min" function (i.e., $(\gamma + 1) \cdot D_{L2M}$) considers the case where it becomes possible to broadcast queueing delay reports directly from MEO satellites to their corresponding LEO satellites earlier than having the LEO satellites to broadcast the same among themselves.

In summary, we have considered two distinct routing update operations. The first operation is globally centralized and is operated by the upper-layer satellites. The second one is locally distributed whereby every satellite is responsible for updating its own routing table and notifying its neighbors (within its own BSA exchange range) of its traffic dynamics.

C. Traffic Reduction Ratio

In the original ELB mechanism, satellites detour X portion of the traffic which was originally destined to S_{busy} by following the routing table for detoured packets. X is calculated based on the Traffic Reduction Ratio (TRR) as per requested by S_{busy}. Accordingly, $(1-X)$ portion of traffic are forwarded via minimum hop paths determined by the normal routing tables. Packets belonging to delay-non-sensitive applications or long delay sessions are detoured at first. The detouring operation can be either via upper-layer satellites (e.g., MEO) or through free neighboring satellites from the same network layer.

A satellite regularly measures its input and output bit rates, denoted by $I(t)$ and $O(t)$, respectively, every T_R time interval. In the original version of ELB, the input bit rate of a given satellite is assumed constant; i.e., equal to the bit rate at the transition time to the busy state. This assumption is not adequate since it does not reflect well the traffic dynamics. We address this issue by recording the history of input bit rates at each satellite N_h times. The value of TRR is computed from this history. Indeed, a satellite, switching to the busy state at a time instant t, calculates the standard deviation of the input bit rate, $\sigma_{\Delta I}(t)$, from the input bit rate history. In addition, the satellite makes an estimate of the maximum input bit rate at the time instant t as follows.

$$I_{max}(t) = I(t) + \frac{\sigma_{\Delta I}(t)}{\sqrt{1-a}} \tag{6}$$

where a is a constant. It should be noted that this equation is derived from the Chebyshev's inequality. The satellite then requests its neighbors to detour a portion χ of traffic computed based on $I_{max}(t)$ as follows.

$$\chi = \frac{O(t)}{I_{max}(t)} \tag{7}$$

Based on the value of χ, each satellite around a busy satellite S_l determines its individual detouring ratio X. On the other hand, an immediate neighbor to S_l sets its detouring ratio to $(1 - \chi)$. A satellite S_i, more than one hop distant from the busy satellite yet within the BSA exchange range of S_l, sets its detouring ratio as follows.

$$X_i = (1 - \chi) \cdot f(A_{i,l}) \tag{8}$$

We observe that the underlying Gaussian distribution sets the detouring ratio of satellites to even higher values as we get closer to the busy satellite.

IV. Performance Evaluation

A. Simulation Setup

In this section, we evaluate the performance of the proposed method in contrast with the original ELB scheme. The performance evaluation is based on computer simulations using the Network Simulator version 2 (NS-2) [8]. A two-layered constellation, consisting of MEO and LEO satellites, is considered. Spaceway NGSO [9] forms the MEO satellite layer that consists of 20 MEO satellites located at an altitude of 10352 km. On the other hand, the LEO constellation comprises 120 satellites with an altitude of 1200 km as per the NeLS system [10]. Both satellite layers are connected via inter-layer ISL links. The capacity of each ISL link is considered to be 25 Mbps. We use drop-tail queues at the satellites. The queue size at each satellite is set to 200 packets. The average packet size of 1Kb is considered in our simulations.

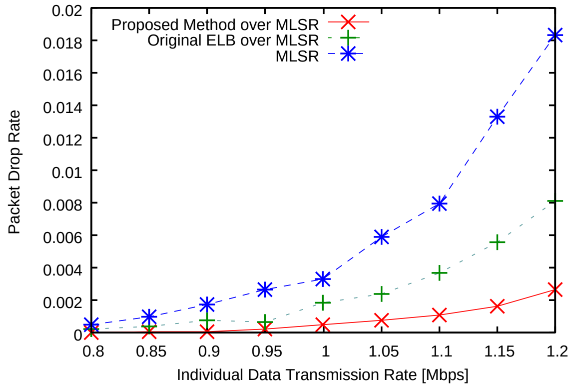

Fig. 3. Packet drops for different individual sending rates.

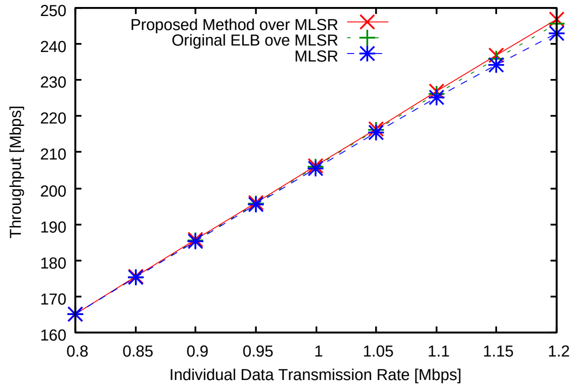

Fig. 4. Total throughput for different individual sending rates.

For generating traffic in the above satellite network topology, 600 non-persistent On-Off flows are simulated. The On/Off periods of the connections are derived from a Pareto distribution with a shape equal to 1.2. The average burst time and the average idle time are both set to 200ms. The ground source and destination nodes are deployed all over the world. 400 out of these 600 flows are distributed as delineated in [11,12] by dividing the world into six regions in order to assume that the communications take place over urban areas. The other 200 terminals are randomly set on the surface of the Earth to simulate communications over suburban areas. The source terminals send data in bursts at constant rates from within the range of 0.8 Mbps to 1.2 Mbps. The data transmissions last for 20 seconds. As comparison terms, the MLSR routing algorithm [7] and the original version of ELB [2,3] are used. Both the original ELB and the proposed method are implemented on top of MLSR.

Normal routing tables are updated every 100s, as in [7]. Satellites monitor their queue lengths and their input/output rates every 20ms (i.e., $\delta = T_R = 20ms$). The parameters related to the link cost computation, β and σ, are arbitrarily set to two and $\frac{1}{3}$, respectively. Other parameters related to the TRR computation, a and N_h are set to 0.5 and 10, respectively. Three quantifying metrics are used, namely the overall throughput, packet drop rate, and traffic distribution index. The latter is defined as follows:

$$f = \frac{(\sum_{k=1}^{N_{ISL}} n_k)^2}{N_{ISL} \sum_{k=1}^{N_{ISL}} n_k^2} \qquad (9)$$

where N_{ISL} denotes the number of ISLs in the constellation (i.e., intra-layer ISLs and inter-layer ISLs). n_k indicates the number of packets that were sent through the k^{th} ISL link during the entire simulation period. The traffic distribution index ranges within zero to one. A traffic distribution index value in the vicinity of one indicates a good distribution of traffic over the entire constellation. In future, we should also consider f_{LEO} and f_{MEO}, distribution index for LEO and MEO, respectively.

B. Simulation Results

First, we evaluate the performance of the proposed method in terms of the total packet drops experienced by the simulated 600 connections during the simulation period. Fig. 3 indicates that the packet drop rates increase with the individual data transmission rates for all three methods. However, in contrast with the contemporary schemes, the proposed method maintains the lowest packet drop rates. In addition, the proposed approach achieves almost no packet loss when low data transmission rates are used.

Fig. 4 plots the total throughputs for different data transmission rates. This figure demonstrates that the proposed scheme outperforms the original ELB and MLSR, and achieves the highest throughput. Furthermore, the proposed method achieves the best traffic distribution as demonstrated by Fig. 5. This is manifested in remarkably high values of the traffic distribution index under the proposed approach, sometimes even twice more than those achieved by the other two schemes.

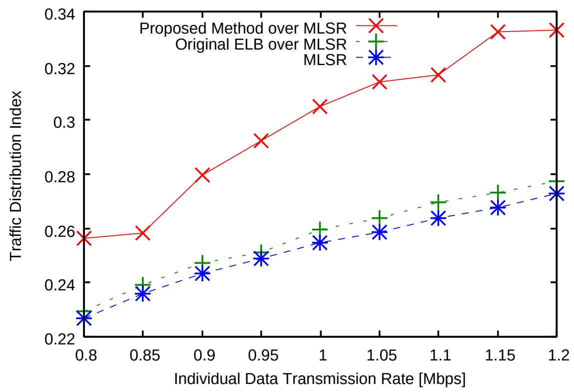

Fig. 5. Traffic distribution index for different individual sending rates.

To investigate how the proposed method responds to traffic dynamics, we simulate a sharp increase in the traffic at a particular satellite by introducing a CBR flow with a large bit rate three seconds after the commencement of the simulation. We plot the variation of inbound traffic (μ) and packet drops (averaged over 100ms) experienced by the satellite during the

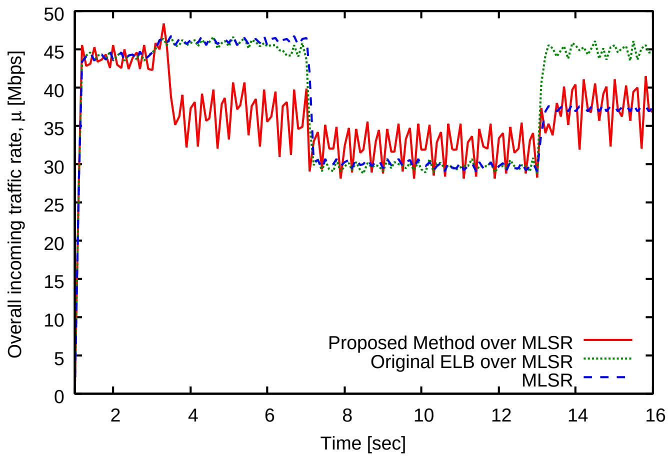

Fig. 6. Inbound traffic variation at a particular satellite over time.

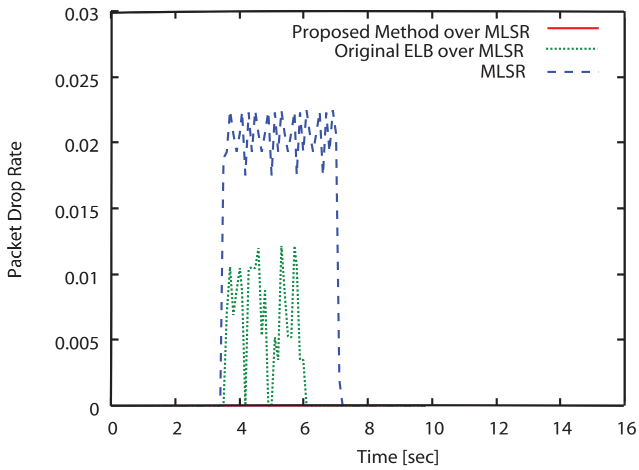

Fig. 7. Packet drop rates at a particular satellite over time.

simulation time, in Figs. 6 and 7, respectively.

Fig. 6 indicates a prompt reaction of the proposed method to the change in traffic as the overall incoming traffic rate at the satellite decreases immediately after the start of the CBR flow. This good performance is due to the fact that satellites around the busy satellite start detouring packets promptly after receiving BSA messages. Although the original ELB also detours packets, the amounts of detoured traffic is indeed much lower. In case of the MLSR algorithm, the routing table is updated periodically and the network is unable to react quickly enough to this sharp increase in data traffic. The packet drops experienced in each scheme are also different as demonstrated in Fig. 7. MLSR, in particular, experiences a high number of packet drops due to the delay in responding to the congestion. On the other hand, though the original ELB experiences less packet drops, its performance is limited in contrast with the proposed scheme. Indeed, the proposed scheme experiences no packet drop and this is more likely attributable to its ability to reflect traffic variations in its unique TRR computation method.

V. Conclusion

In this paper, we re-designed the ELB scheme for multi-layered satellite networks. The suggested enhancements pertain to i) the ranges for exchanging signaling messages, ii) the routing table update operations, and iii) the detouring ratio computation method. Computer based simulations are conducted and encouraging results are obtained. The results demonstrate that the proposed enhancements to ELB are indeed effective in terms of avoiding packet drops, alleviating congestion, enhancing throughput, and efficiently distributing traffic over the satellite constellation. In addition, we have also verified the robustness of the proposed scheme to traffic dynamics.

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