Explicit Load Balancing Technique for NGEO Satellite IP Networks With On-Board Processing Capabilities

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***Abstract*—Non-geostationary (NGEO) satellite communication systems offer an array of advantages over their terrestrial and geostationary counterparts. They are seen as an integral part of next-generation ubiquitous communication systems. Given the non-uniform distribution of users in satellite footprints, due to several geographical and/or climatic constraints, some Inter-Satellite Links (ISLs) are expected to be heavily loaded with data packets while others remain underutilized. Such scenario obviously leads to congestion of the heavily loaded links. It ultimately results in buffer overflows, higher queuing delays, and significant packet drops.**

To guarantee a better distribution of traffic among satellites, this paper proposes an explicit exchange of information on congestion status among neighboring satellites. Indeed, a satellite notifies its congestion status to its neighboring satellites. When it is about to get congested, it requests its neighboring satellites to decrease their data forwarding rates by sending them a self status notification signaling message. In response, the neighboring satellites search for less congested paths that do not include the satellite in question and communicate a portion of data, primarily destined to the satellite, via the retrieved paths. This operation avoids both congestion and packet drops at the satellite. It also ensures a better distribution of traffic over the entire satellite constellation. The proposed scheme is dubbed "Explicit Load Balancing" (ELB) scheme.

While the multi-path routing concept of ELB has many advantages, it may lead to persistent packet reordering. In case of connection-oriented protocols, this phenomenon results in unnecessary shrinkage of the data transmission rate. A solution to this issue is also incorporated in the design of ELB. The interactions of ELB with mechanisms that provide different QoS by differentiating traffic (e.g., Differentiated Services) are also discussed. The good performance of ELB, in terms of better traffic distribution, higher throughput, and lower packet drops, is verified via a set of simulations using the Network Simulator (NS).

***Index Terms*—Congestion alleviation, load balancing, NGEO satellite network, routing, traffic engineering.**

I. Introduction

DESPITE the recent advances in terrestrial communication technologies, the ever-growing community of Internet users poses serious challenges to current terrestrial networks. Terrestrial networks are expected to provide a plethora of bandwidth-intensive services, with different Quality of Service (QoS), to a potential number of users, dispersed over extensively wide areas and requiring different degrees of mobility. To cope with this issue, network technicians and telecommunication operators have envisaged optical-fiber networks and have considered temporary solutions such as Asynchronous Digital Subscriber Line (ADSL) and High-rate DSL (HDSL) technologies. However, as the demand for advanced multimedia services is growing in terms of both the number of users and the services to be supported, applying such solutions to bridge the last mile between local service providers and end-terminals will require an immense investment in terms of time, infrastructure, and human resources. Building a cost-efficient global ubiquitous infrastructure is one of the major challenges before telecommunication industries in the current century. In this regard, and considering the fact that more than half of the world lacks a wired network infrastructure, satellite communication systems are seen as an attractive solution. The efficiency of satellite-based broadband services is strongly remarkable in remote zones and low-density population areas.

The key technologies required to support broadband communications over satellite systems have been already developed [1], [2]. Indeed, with the recent advancements in satellite return channels and on-board processing technologies, satellites are now able to provide full two-way services to and from earth terminals [3]. Additionally, several techniques for on-demand onboard switching have been proposed to make efficient use of satellites capacity [4]. Unlimited connectivity can be accordingly guaranteed. The advent of ka-band guarantees more availability of spectrum to support broadband multimedia communication [5], [6]. This has spurred further on the expansion of multimedia satellite networks. To encourage the deployment of cost-effective terminals with small antennas (e.g., Very Small Aperture Terminals (VSATs) and Ultra Small Aperture Terminals (USATs)), satellite channels with higher frequencies, such as V-band (36–51.4 GHz) and millimeter wave (71–76 GHz), have also been developed. These high frequencies will enable scalable mobility and ubiquitous connectivity across the world. Various mechanisms have also been proposed to cope with the well-known problems associated with rain and atmospheric attenuation at these frequencies. Given these advancements and on-going enhancements in satellite communications, it is now possible to design and implement satellite based communication systems for high bit rate services.

Satellite communication systems exhibit unique features and offer an array of advantages over traditional terrestrial networks.

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In addition to their inherent multicast capabilities and flexible deployment features, they are able to provide coverage to extensive geographic areas and to interconnect among remote terrestrial networks (e.g., islands). They can be also used as an efficient alternative to damaged terrestrial networks to recover from natural disasters. In the recent literature, a significant number of satellite communication constellations have been thus proposed using Geostationary (GEO), Medium Earth Orbit (MEO), or Low Earth Orbit (LEO) satellites.

In addition to their long propagation delays, GEO systems cause mobile terminals in high latitude regions to experience frequent cut-offs of propagation signals by tall buildings, trees, or mountains possibly due to low elevation angles of the link above the horizon. To provide global communication with reasonable latency and low terminal power requirements, constellations made of multi Non-Geostationary (NGEO) satellites (e.g., LEO and MEO) have been the focus of several researches in the recent literature [7].

Due to geographical and/or climatic constraints, the community of future NGEO satellite users will exhibit a significant variance in its density over the globe. Indeed, satellites covering urban areas dense with users will be more congested than satellites serving rural regions. This density variance, along with the highly dynamic feature of NGEO constellations, will yield a scenario where some satellite links are congested while others are underutilized. In the absence of an efficient routing algorithm that takes into account the traffic distribution, this unfair distribution of network traffic will lead to significant queuing delays and large number of packet drops at the congested satellites. Obviously, such performance will lead to poor throughput and will ultimately affect the QoS credibility of the entire system. All in all, support for IP routing in the satellite constellations is highly important for the implementation of Integrated or Differentiated Services (DiffServ) architectures to support QoS over satellite systems.

In the recent literature, a number of pioneering routing protocols have been specifically proposed for satellite networks. Most of these protocols search for the shortest path with the minimum routing cost. As will be discussed in the next section, a highly missing point in their design consists in their focus on searching for the shortest path with the minimum routing cost without any consideration of the total traffic distribution over the entire constellation. Indeed, while searching for only short paths for communication, some satellites may get congested while others are underutilized. This phenomenon leads to unfair distribution of the network traffic and ultimately to higher queuing delays and significant packet drops at some satellites in the constellation.

To cope with the aforementioned limitation of current routing protocols, this paper suggests that neighboring satellites should explicitly exchange information on their current congestion status. An Explicit Load Balancing (ELB) technique is developed. In ELB, a satellite continuously monitors its queue size to determine its state which may be free, fairly-busy, or busy. A change in the state of a satellite is immediately notified to its neighboring satellites via a Self-State Advertisement packet. As a consequence, the cost of the links between the busy satellite and its neighbors is then increased. To avoid an imminent congestion, a satellite with high traffic load requests its neighboring satellites to forward a portion of data, originally destined to travel through the satellite, via alternative paths that do not involve the satellite. The ELB scheme therefore alters the traffic sending rate of neighboring nodes of the satellite in question before it gets congested. Since minimum cost links are preferred, packets will be routed on the least loaded links and busy links will therefore have less packets in the queues.

In the ELB mechanism, satellites use three parameters to indicate their congestion status and to reduce their data transmission rates, respectively. These parameters consist of two queue ratio thresholds and a traffic reduction ratio, respectively. Appropriate adjustments of the parameters would result in efficient distribution of traffic over multi-hop satellite constellations. In this paper, we describe an easy-to-implement mathematical model for a dynamic setting of the system parameters. While an abridged version of the proposed scheme can be found in [8], the major improvements presented in this paper consists in the application of the proposed scheme in more general scenarios where both delay-sensitive and delay-insensitive applications coexist. Furthermore, we investigate the effect of packet reordering on the working of the Transmission Control Protocol (TCP) when ELB is in use.

Indeed, while having packets of the same flow transmitted over different links helps to better distribute the traffic over the satellite constellation, and accordingly alleviates congestion and avoids packet drops, it leads to the reception of packets in an out-of-order manner at the receiver side. In case of TCP, this phenomenon results in the transmission of duplicate acknowledgments, unnecessarily halves the congestion window of TCP, and ultimately degrades the throughput. As a remedy to this issue, we suggest some minor modifications to the TCP implementation at the receiver side to enable receivers to judge the actual reason beneath the out of order reception of packets. Simulations are conducted to evaluate the performance of the proposed packet reordering recovery mechanism against that of standard TCP and TCP-PR (Persistent Reordering) [34], a recently proposed scheme for persistent packet reordering. In light of the complexity and significant overhead of TCP-PR (compared to our proposed control mechanism), guidelines on which scheme to use are given while taking into account traffic characteristics, namely the ratio of delay-non sensitive traffic rate to that of delay-sensitive traffic, and the satellite constellation type (LEO or MEO).

Furthermore, as packets have to traverse more hops in ELB, delay-sensitive applications may get affected by the extra delay due to additional hops. To cope with such an issue, we consider the use of differentiated services and classify users into a number of classes, namely delay sensitive, throughput-sensitive, and best effort. Via simulations, we demonstrate the efficiency of ELB in such environments.

The remainder of this paper is organized as follows. Section II presents a detailed survey on the state-of-art in the context of routing protocols for multi-hop NGEO satellite constellations. The key design philosophy and distinct features that were incorporated in the proposed scheme are described in Section III. The dynamic settings of its parameters are also discussed in the section. The performance of ELB is evaluated and compared to other schemes in Section IV. The paper concludes in Section V with a summary recapping the main advantages and achievements of the proposed architecture.

II. Related Work

While use of Inter-Satellite Links (ISLs) in multi-hop NGEO constellations provides more flexibility, it leads to complex dynamic routing [9]. The routing complexity becomes more substantial as NGEO satellites change their coverage areas on the Earth surface due to their continuous motion, and accordingly have to transmit different amounts of traffic load. This ultimately results in an unbalanced distribution of the total traffic over the entire constellation.

To route traffic over dynamic satellite constellations, several strategies have been proposed. Dynamic Virtual Topology Routing (DVTR) [10] and Virtual Node (VN) [11] protocols are the best known concepts. Based on these two schemes, important research efforts have been elaborated in the recent years with respect to IP proprietary routing over satellite constellations. In [12], the authors provide a thorough discussion on the main credits and downfalls of these routing protocols.

In general, a communication delay consists of both propagation and processing/queuing delays. In the context of satellite networks, numerous researchers presume that the propagation delay is the dominating factor in the communication delay. They have thus focused on developing routing mechanisms that find minimum propagation delay paths with minimal hop count for communication. In [13], a routing strategy for maximizing throughput in LEO satellite networks is proposed. The proposed strategy consists of an algorithm that finds the minimum hop path using Dijkstra's algorithm and a scheduling mechanism that favors packets destined to nearby destinations. While the scheduling mechanism maximizes the throughput, it yields poor fairness against packets destined to distant destinations. Henderson *et al.* [14] propose an onboard distributed routing protocol that selects the next hop based on minimization of the remaining geographic distance to the destination. In other words, depending on the geographic information embedded in the addresses, each satellite forwards the packet to its neighbor that most reduces the distance to the destination. This series of locally optimal forwarding decisions will establish a route that is close to the optimal route. Another vision for path minimization consists in favoring ISLs with higher lifetime to reduce the additional delays that may be caused by ISLs handovers [15], [16].

While the recent literature has known a potential number of routing protocols that search for paths with the shortest delays, these protocols may turn unfavorable for the support of certain QoS requirements. They may be appropriate for only best-effort light-load traffic. For better QoS conditions, the routing algorithm should distribute the traffic in a balanced way over appropriate ISLs between end-terminals [1]. This operation can be performed in either a central or a distributed manner. In case of the former, an ingress node (e.g., a terrestrial node or a satellite) calculates the route to the destination node. Traffic information is gathered either locally from nodes in the vicinity of the node where routing is performed or globally from the whole network [18]. While the latter operation is more traffic adaptive, it incurs significant computational and signaling complexity. In addition, central traffic distribution techniques generally do not scale well as the size of the network increases. They also introduce extra signaling delays as the gathered information takes significant time, due to high propagation delays, till it is distributed in the constellation. Therefore, it does not accurately reflect the actual condition of the network.

To cope with this issue, a distributed next hop routing strategy seems to be an interesting solution. In such distributed load balancing techniques, satellites independently decide on the best next hop to which packets should be forwarded. The research work outlined in this paper falls in this category. In [19], a priority-based adaptive minimum-hop routing algorithm is proposed. Similar to the aforementioned routing algorithms, the common issue among conventional distributed load balancing techniques consists in the fact that the route decision is based primarily on propagation delay. Given the fact that queuing delays may also contribute largely to the total delay that a packet may experience, mainly in case of heavy loads, a more appropriate routing cost metric has to be selected. In this context, [20] proposes a Minimum Flow Maximum Residual (MFMR) routing protocol where the minimum-hop path with the minimum number of flows is selected. One of the main drawbacks of the protocol consists in the fact that it implies knowledge of the flows over the constellation and does not consider the case where the flows count increases along the selected path. Given the fast motion of satellites, such scenario may occur frequently. This would lead to the congestion of the chosen MFMR paths and ultimately results in unfavorable performance. In [21], a Probabilistic Routing Protocol (PRP) is proposed. The PRP scheme uses a cost metric as a function of time and traffic load. The traffic load is assumed to be location homogeneous. The major pitfall of the protocol consists in this assumption as it is far away from being realistic. Indeed, newly coming traffic can easily congest the chosen PRP path and leave other resources underutilized. In [22], Jianjun *et al.* propose a Compact Explicit Multi-path Routing (CEMR) algorithm based on a cost metric that involves both propagation and queuing delays. At a given satellite, the queuing delay is predicted by monitoring the number of packets in the outgoing queue of the satellite over a time interval. It is assumed that the network state over each time interval is updated before routing calculation is carried out. While the used cost metric gives a good insight about the queuing delay that may be experienced by a packet at a given satellite, it does not reflect the congestion state of the next hop, nor does it estimate the queuing delay a packet may experience there. It does not reflect the likelihood of packets to be dropped by the downstream hop either. Taking these remarks into account, the research work outlined in this paper aims at developing a routing strategy where packet drops are avoided and traffic burden is efficiently and fairly distributed among all participating satellites.

III. Operational Overview of the ELB Scheme

This section presents a detailed description of the proposed ELB scheme, the rationale behind the setting of its parameters, and its interactions with service differentiating mechanisms. Adequate measures to cope with the issue of packet reordering in connection-oriented protocols, such as TCP, are also portrayed. For the sake of simplicity, we first consider the case of a single traffic class. The working of the proposed scheme in the case of multiple traffic classes will be addressed later in this section.

The envisioned multi-hop NGEO satellite constellation consists of S satellites with on-board processing capabilities, uniformly distributed over N orbits, forming a mesh network topology. Each satellite is able to set up a maximum of M links with its neighboring satellites. These links are called Inter Satellite Links (ISLs). Satellites are assumed to be aware of their neighboring satellites.

To reflect the congestion state of a satellite, three representative states are defined based on the current queue occupancy of the satellite. The choice of the queue occupancy to indicate the congestion state of satellites is similar in spirit to major intelligent packet discarding schemes such as the well known Random Early Discard (RED) [23], Random Early Marking (REM) [24], and Explicit Congestion Notification (ECN) [25]. A common feature among most of these queue length based Active Queue Management (AQM) schemes consists in the computation of the average buffer occupancy (or queue length) as the Exponentially Weighted Moving Average (EWMA) of the instantaneous queue length at the time of each packet arrival. In contrast to this, and similar to some recently proposed transport protocols [27], [28], the proposed ELB scheme considers the use of persistent queue length to indicate congestion. In essence, the persistent queue length is defined as the sustained buffer occupancy of a satellite during a time interval. This computation solves the heuristics in the EWMA parameter setting and can be easily implemented in satellites with much less computational demand than EWMA.

It should be stressed out that the rationale behind the use of persistent queue lengths as an estimator of congestion consists in the simplicity of the concept and its wide implementation as a large number of router vendors are using a quite number of queue length-based AQM methods. Admittedly, the efficiency of AQM methods based on queue length depend on the buffer space [26]. It is suggested that in order to accommodate well traffic, routers should acquire an amount of buffer space equal to twice the bandwidth delay product, in other words equal to the link capacity from when the congestion is detected by the router till when the traffic is decreased by the sender. In our ELB scheme, the congestion notification is performed in one direction and locally; only neighboring satellites that are involved in it. Considering the worst scenario case where congestion has already occurred (recall that the ELB scheme is designed to anticipate congestion and to inform neighboring satellites before congestion occurrence), the required buffer space would be equal to an amount of only the product of one-hop ISL delay and the ISL bandwidth. In case of smaller buffer sizes, use of queue lengths can be easily substituted by information on packet drops and link idle events to estimate congestion at satellites as in the Blue scheme [26].

The state of a satellite is marked as Free State (FS) when the queue ratio of its current queue occupancy to the total queue size, Qr, is inferior to a pre-defined threshold α. The satellite is considered to be in a Fairly Busy State (FBS) when its queue ratio is between the threshold α and another predetermined threshold β. The satellite is considered to be in a Busy State (BS) if its queue ratio exceeds the threshold β.

From the observation that a better load balancing can be achieved provided that satellites are aware of the traffic conditions of their neighboring satellites, in ELB satellites are designed to mutually and dynamically exchange information on the states of their queue occupancies. Indeed, when a given satellite A experiences a state transition from free to fairly busy, it sends a warning message to its neighboring satellites informing them that it is about to get congested. The neighboring satellites are then requested to update their routing tables and start searching for alternate paths that do not include satellite A. When the satellite enters the busy state, it transmits a Busy State Advertisement (BSA) signaling packet requesting the neighboring satellites to reduce their sending rates of traffic destined to satellite A by a ratio χ. The $(1-\chi)$ portion of traffic data will be transmitted via alternate paths retrieved earlier. The BSA signaling packet carries information on the satellite identifier (ID) and the Traffic Reduction Ratio (TRR) χ.

It should be stressed out that warning messages and BSA packets do not incur any significant overhead, in terms of neither bandwidth consumption nor scalability, as they are broadcasted merely upon a state transition and only to the neighboring satellites (maximum M satellites) not over the entire connection path. The next subsections portray the setting procedure of the Queue Ratio thresholds α and β, and the TRR parameter χ.

A. Setting of Queue Ratio Thresholds

The key philosophy behind an optimum setting of β and α is to reflect the packet discarding probability in these two parameters so as to avoid packet drops when a satellite is running under heavy loads. Let I and O denote the total input and output traffic rates at a given satellite, respectively. Let Q_l and $q(t)$ denote the total length of its queue and the occupancy of its queue at time t, respectively. Assuming that the input and output traffic rates constant over a short period of time, the elapsing time till a packet drop occurs can be expressed as follows:

$$\delta_d = \frac{(Q_l - q(t)) \cdot P_{\text{avg}}}{I - O} \tag{1}$$

where P_{avg} is the average packet size. If the satellite is assumed to monitor its queue occupancy every δ interval time, it needs a maximum of $(\delta + d)$ time to notify its neighboring satellites of a possible packet drop, where d denotes the ISL delay. In this case, two scenarios can be envisioned:

- $\delta_d \leq \delta + d$: Packet drops happen before neighboring satellites are notified and adequate measures are taken. In this case, the packet dropping probability is one $(p = 1)$.
- $\delta_d > \delta + d$: In this case, if the satellite keeps receiving and transmitting data at the same rates over a number of monitoring intervals, packet drops happen only once during $(\frac{\delta_d}{\delta+d})$ times of monitoring operations. The packet dropping probability is thus $(\frac{\delta+d}{\delta_d})$.

In both cases, the packet dropping probability can be expressed as

$$p = \mathrm{Min}\left(1, \frac{\delta + d}{\delta_d}\right). \tag{2}$$

To reflect the packet dropping probability in the setting of β, we set β to $(1-p)$

$$\beta = 1 - p. \tag{3}$$

The rationale behind this setting is that when traffic load gets heavy and p gets higher values, β should be set to small values so as the satellite would quickly transit to the busy state and neighboring satellites would be promptly requested to reduce their sending rates to avoid possible congestion and packet drops. In this regard, it should be noted that setting the monitoring interval δ to high values may lead to significant packet drops. Indeed, in case of long monitoring intervals, by the time a satellite monitors its queue length, congestion may have already occurred and packet drops become then inevitable. In such case, the packet dropping probability will be equal to one $(p = 1)$. Consequently, β will be always set to zero. As a remedy to this issue, the satellites are assumed to monitor their queues in a real time fashion. Therefore, δ is set to 1 ms throughout this paper.

An optimum setting of the threshold α is a tradeoff between two fold. First, with small values of α, neighboring satellites can be granted a time long enough to carry out their search for alternative paths before they are asked to detour their traffic from the congested satellite. Second, with high values of α, neighboring satellites are requested to search for alternative paths only when it is necessary, in other words less frequently. This improves the warning accuracy and reduces the overhead that may result in case of frequent searches for alternative paths. Considering these two observations and for the sake of the scheme simplicity, α is set to half of β

$$\alpha = \frac{\beta}{2}. \tag{4}$$

B. *Setting of the Traffic Reduction Ratio*

The main objective behind the setting of the TRR parameter is to allow satellites to return back to their free state and reside in this state for at least a predetermined period of time θ. Let I_t and I_s denote the total rate of traffic coming from terminals within the coverage area of a satellite and that of traffic coming from neighboring satellites, respectively (Fig. 1). When the satellite shifts to the busy state, it requests neighboring satellite to reduce their sending rates. By the time the BSA signaling packet reaches the neighboring satellites, the queue occupancy of the satellite is

$$q(t_{\mathrm{BSA}}) = \mathrm{Min}\left(Q_l \cdot \beta + \frac{d \cdot (I_s + I_t - O)}{P_{\mathrm{avg}}}, Q_l\right). \tag{5}$$

So as that the satellite is ensured a prompt recovery and a residual time in the normal state for at least θ time, the new

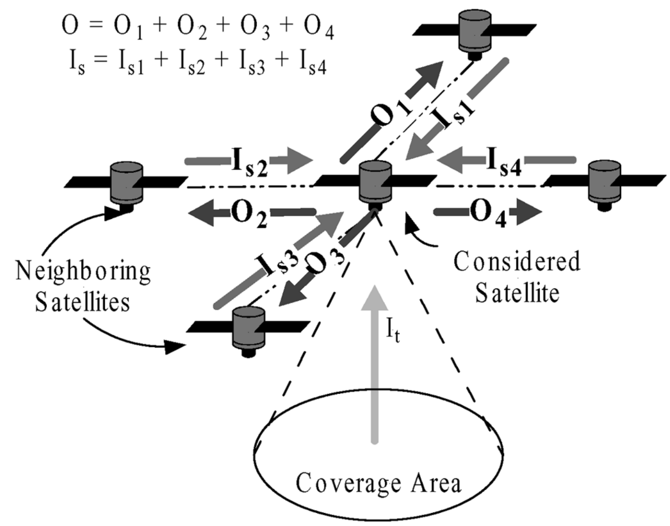

Fig. 1. Rates of Traffic coming from neighboring satellites and terrestrial terminals.

rate of traffic coming from neighboring satellites, I_s^{new}, should satisfy the following equation:

$$(I_s^{\mathrm{new}} + I_t) - O = \frac{P_{\mathrm{avg}} \cdot (q(t_{\mathrm{BSA}}) - Q_l \cdot \alpha)}{\theta}. \tag{6}$$

The TRR parameter can be accordingly computed as

$$\chi = \mathrm{Min}\left(\mathrm{Max}\left(0, \frac{I_s^{\mathrm{new}}}{I_s}\right), 1\right). \tag{7}$$

By this setting, a long enough recovery time can be granted for satellites before they enter again the busy state and request their neighboring satellites to reduce further their sending rates.

Traffic forwarding may cause loops. Indeed, as previously explained, to avoid the congestion of a satellite, neighboring satellites are requested to transmit a portion of traffic data via paths that do not include the satellite in question. At this stage, the system should ensure that the detoured portion of traffic does not experience further detouring along the selected paths till the destination. To cope with the issue of traffic redistribution cascading, we use a routing metric that instantly reflects both the one-way propagation delay and the instant queuing delay. This is similar in concept to the idea of CEMR [22]. We assume that routing tables are updated periodically every Δ interval time. At time t, the instant path cost is defined as

$$L_{\mathrm{cost}}(t) = T_d + T_B(t) \tag{8}$$

where T_d denotes the one-way propagation delay. $T_B(t)$ denotes a predicted value of the queuing delay at time t and is computed as follows:

$$T_B(t) = \frac{1}{\Delta} \times \int_{t-\Delta}^{t} q(i) \times \frac{P_{\mathrm{avg}}}{C} \times di \tag{9}$$

where C denotes the ISL capacity.

C. ELB in the Presence of Multiple Traffic Classes

So far we have considered the working of ELB in case of a single traffic class. Furthermore, we did not ponder on the sensitivity of traffic to delay. As a matter of fact, the ELB scheme can decrease the number of packet drops by detouring traffic when congestion occurs and can accordingly improve traffic distribution in the network. However, the detoured packets may experience extra delay due to increase in hop count. This phenomenon may be unfavorable for delay sensitive traffic such as real-time applications. To cope with this issue, delay sensitive traffic must be differentiated from delay tolerant background traffic.

In this regard, this paper proposes the classification of traffic according to the application type to prevent delay-sensitive applications from additional delay. This is possible by the use of any service differentiating mechanism (e.g., DiffServ). In the presence of multiple traffic classes, delay insensitive applications are to be first forwarded via the alternate paths to avoid imminent congestion, leaving bandwidth room for packets of delay-sensitive applications that can be transmitted via the otherwise-congested satellites if that would guarantee the delay requirements of the applications.

Service differentiating policies are vital for the provision of QoS in satellite networks. Given the processing limitations of satellites, these policies should be both simple and fast. In this paper and similar to [17], users are simply classified into three classes as follows:

- Traffic class A (delay-sensitive): Typical applications include interactive real-time applications, such as Voice over IP (VoIP) and interactive video applications, which are delay-sensitive applications.
- Traffic class B (throughput-sensitive): Representative applications are Video on Demand (VoD) and large file distribution which require high throughput.
- Traffic class C (best effort): This traffic class represents best-effort services as known in Internet and includes applications without any specific requirements.

As previously explained, a satellite implementing ELB constantly monitors its inbound traffic. In the presence of multiple traffic classes, ELB calculates the traffic percentage of each class in the total traffic. Based on the measured values and using the EWMA method, ELB makes an approximate estimate of the traffic percentages of each class in the next monitoring interval time. The computation is performed as follows:

$$\bar{N}_i(n) = \omega N_i(n) + (1-\omega)\bar{N}_i(n-1) \quad i \in \{A, B, C\} \tag{10}$$

where $N_i, \overline{N_i}$, and ω denote the measured value of the traffic percentage of class i, its estimated value, and a smoothing constant from the interval $[0, 1]$. Admittedly, the setting of the latter is subjective (e.g., 0.2 in [28] and 0.002 in [23]). Indeed, a too large value of ω produces smoother estimation but results in sluggish response to sudden changes in traffic conditions. On the other hand, a too small value of ω weakens the estimation accuracy.

Considering the aforementioned traffic classification method, packet detouring is carried out according to the predicted traffic percentage of each traffic class using. Upon reception of a BSA signaling message from its neighboring satellite, a satellite starts detouring first packets of class C. If the requested detouring ratio of traffic $X (X = 1 - \chi)$ is larger than the traffic percentage of class C, the traffic of class B is detoured as well. The delay-sensitive traffic of class A always traverses the default path that is determined by the routing protocol in use (e.g., Dijkstra) and is not detoured. Denoting the predicted traffic ratios of classes A, B and C as a, b and c, respectively, traffic detouring is carried out as shown in Table I. In all scenarios, packets of delay-sensitive applications are exempted from the detouring operation of ELB. In this manner, they are avoided any increase in their communication delay. In addition, from the observations that today's Internet traffic is characterized by the dominance (more than 80% [29]) of delay-nonsensitive traffic, it is more likely that traffic of class A would be minimal compared to the traffic of other classes. Its influence on network congestion is expected to be minimal as well.

TABLE I
PACKET DETOURING RATIO AS FUNCTION OF THE TRAFFIC RATIO OF THE THREE ENVISIONED CLASSES

Traffic class / Packet detouring ratio	A	B	C
$X < c$	0	0	X/c
$c \leq X < (b+c)$	0	$(X-c)/b$	All
$(b+c) \leq X$	0	All	All

D. TTL-Based Enhanced Acknowledgment Mechanism for Packet Reordering

Algorithm 1 Pseudo Code of the Proposed Packet Reordering Recovery Mechanism

```
Upon packet arrival
if Packet arrival in order then
    Store TTL = TTL_in-order
    Reset timer
    Send back ACK
else
    Check new TTL
    if TTL ≥ TTL_in-order then
        Set a timer
        if Timer expires then
            Send DupACK
        else
            Send normal ACK
        end if
    else
        Send DupACK
    end if
end if
```

When ELB is in use, packets of the same flow are transmitted over multiple paths upon congestion. While this multi-path routing of ELB has many advantages (e.g., better distribution of traffic, congestion alleviation, and avoidance of packet drops), it makes packets of same application experience different latencies, resulting in out-of-order delivery to the final destination and delay jitter. For connectionless-oriented protocols such as User Datagram Protocol (UDP), this issue can be easily resolved by buffering capabilities. Indeed, a small buffer at end terminals can ensure coherent reception, remove the jitter added by the network, and recover the original timing relationships between the transmitted data. For applications based on connection-oriented protocols (e.g., Transmission Control Protocol—TCP), such disorder in packet reception results in the transmission of unnecessary duplicate acknowledgments (DupAcks). Indeed, current implementations of TCP work on the assumption that out-of-order packets indicate network congestion. TCP senders mistakenly halve their congestion windows when packets are reordered. In case of New Reno based TCP variant, Partial ACKs (ParACKs) are used to indicate the occurrence of multiple losses in a single window. Upon reception of a ParACK, the sender retransmits the lost packet and waits for an ACK to come back. To retransmit multiple lost packets, multiple Round Trip Times (RTTs) are thus required. This, coupled with the fact that satellite links exhibit relatively long delays, means that the TCP sender may necessitate a long time to increase its congestion window to its value before entering the fast retransmit phase. This leads to a drastic under-utilization of the network resources.

Packet reordering phenomena has been observed in today's Internet as well [30]. In recent literature, a number of approaches have been devised for improving the performance of TCP in environments prone to packet reordering [31]–[33]. The most pioneering method is the TCP-PR (TCP for Persistent Reordering) scheme presented in [34]. The key idea behind TCP-PR consists in the detection of packet losses through the use of timers rather than duplicate acknowledgments. Indeed, packets are assumed to be lost only if their corresponding acknowledgments do not arrive within a predefined time. In the design of TCP-PR, worst-case analysis and Internet traces are referred to for an appropriate setting of timers. While TCP-PR is a window based congestion control mechanism, its working follows totally different rules than standard TCP. At the receiver side, it does not require any modifications. However, it adds significant complexity and incurs important overheads, in terms of both computation and memory, at the sender side. Additionally, it is yet not clear enough how the parameters of the proposed scheme should be selected for a stable operation.

As a remedy to packet reordering in ELB, we suggest that receivers refer to the TTL field of packet headers to judge whether the out of order in the reception of packets is due to congestion or simply to changes in the communication path. In case of IPv6, the use of the TTL field can be substituted by the Hop Limit field. Algorithm 1 portrays the pseudo code of the proposed packet reordering recovery mechanism.

Upon reception of a packet in order, a TCP receiver immediately sends back a normal ACK to the sender similar to the ordinary behavior of TCP. The receiver records then the TTL information available at the header of the received packet as $TTL_{\mathrm{in-order}}$. When the receiver receives a packet in out-of-order, two cases can be envisioned. If the number of hops traversed by the received packet is the same or smaller compared to the previously received packet, in other words

$$TTL \geq TTL_{\mathrm{in-order}} \tag{11}$$

the receiver interprets the incident as due to changes in the communication path. Acknowledgment packets are hold for a time interval. In this way, throughput degradation due to unnecessary transmission of duplicate ACKs can be prevented. If the missing packet does not arrive within the time interval, retained ACKs are returned requesting the TCP sender to retransmit the missing packets.

If the inequality (11) does not hold, the currently received packet was transmitted through a longer path than the previously received packet. Therefore, the receiver judges the out of order reception of packets as due to a packet discard and returns a duplicate acknowledgment. In other words, it proceeds in the same way as an ordinary TCP receiver. The sender retransmits the dropped packets and reduces its window size to half. Observe that the proposed operation can be accomplished without changing the protocol and requires a merely simple modification at only the receiving terminal. It is thus compatible with any TCP sender.

IV. Performance Evaluation

A. Simulation Setup

In this section, we evaluate the performance of the ELB scheme using the Network Simulator (NS) [35]. We consider an Iridium-like constellation. The constellation is formed of 66 satellites evenly and uniformly distributed over six orbits. In the considered constellation, we do not consider the seams where two ISLs are switched off due to the motion in opposite directions. Thereby, it is assumed that at any time each satellite maintains four ISLs with its neighboring satellites. Uplinks, downlinks, and ISLs are each given a capacity equal to 25 Mbps ($C = 25$ Mbps). In all conducted simulations, all links are presumed to be error-free. The rationale beneath this assumption is to avoid any possible confusion between throughput degradation due to packet drops (due in turn to buffer overflows at satellites) and that due to satellite channel errors. While such an assumption does not hold in real networks, results of simulations conducted in environments with channel errors demonstrated that link errors do not change any of the fundamental observations made about the proposed ELB scheme. The same thing applies to the performance of ELB in environments with varying ISL delays. For this reason, unless otherwise stated the delays of ISL links are all set to a constant value, 20 ms ($d = 20$ ms). With no specific purpose in mind, the average packet size is set to 1 KB ($P_{\mathrm{avg}} = 1$ KB). Drop-Tail based buffers of lengths equal to 200 packets are used ($Q_l = 200$ pkts).

For traffic generation, we consider 600 non-persistent On-Off flows. The On/Off periods of the connections are derived from a Pareto distribution with a shape equal to 1.2. The average burst

TABLE II
DISTRIBUTION OF END-TERMINALS OVER THE SIX CONTINENTAL REGIONS

Source	Destination					
	N.America (%)	S.America (%)	Europe (%)	Africa (%)	Asia (%)	Oceania (%)
N.America (%)	60	10	15	2	10	3
S.America (%)	35	40	12	2	8	3
Europe (%)	40	5	40	2	10	3
Africa (%)	40	2	30	20	5	3
Asia (%)	20	2	10	2	50	6
Oceania (%)	40	2	10	2	12	34

time and the average idle time are set to 200 ms. The source and destination end-terminals are dispersed all over the Earth, divided into six continental regions, following a distribution identical to the traffic distribution used in [36], [37] (Table II). The sources send data at constant rates from within the range of 0.8 Mbps to 1.5 Mbps.

In the performance evaluation, we use the Dijkstra's Shortest Path (DSP) algorithm and CEMR as comparison terms. While the ELB scheme can be implemented over any routing protocol, we consider two implementations of the scheme; one over DSP and the other over CEMR. Our implementation of CEMR is based on the scheme description in [22]. Similarly to the paper, the routing cost metrics of CEMR and ELB are updated every 1s interval of time ($\Delta = 1$ s). The performance of the schemes is evaluated in terms of the achieved total throughput and the experienced total packet drops. To investigate how well traffic is distributed over the entire constellation, the following traffic distribution index is used:

$$f = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n\sum_{i=1}^{n} x_i^2} \tag{12}$$

where n is the number of ISLs and x_i denotes the actual number of packets that traversed the ith ISL. This index ranges from zero to one and indicates how well the traffic is distributed over the constellation. Low values of the traffic distribution index represent poor distribution of traffic over the constellation. Simulations are all run for 60s. In the conducted simulations, satellites monitor their current queue occupancy in a real time fashion ($\delta = 1$ ms). Finally, unless otherwise specified, the desired time for a satellite to reside in the Free state after a transition to the Busy state θ is set to 200 ms (e.g., deliberately set to ten times the ISL delay).

B. Simulation Results

1) Single Traffic Class: First, we consider the case of a single traffic class. To investigate the abilities of the ELB scheme in supporting QoS, we evaluate its performance in terms of the achieved throughput and the total packet drops experienced by the simulated 600 connections. Fig. 2 graphs the total number of packet drops experienced by all the connections during the entire simulation course and that is for different sending rates of the connections. For all the considered bit rates, the implementation of ELB over CEMR shows the best performance as it achieves the lowest packet drop rate. Note also that even the implementation of ELB over DSP avoids more packet drops than the other two routing protocols, DSP and CEMR. This indicates an important feature of the ELB scheme in avoiding

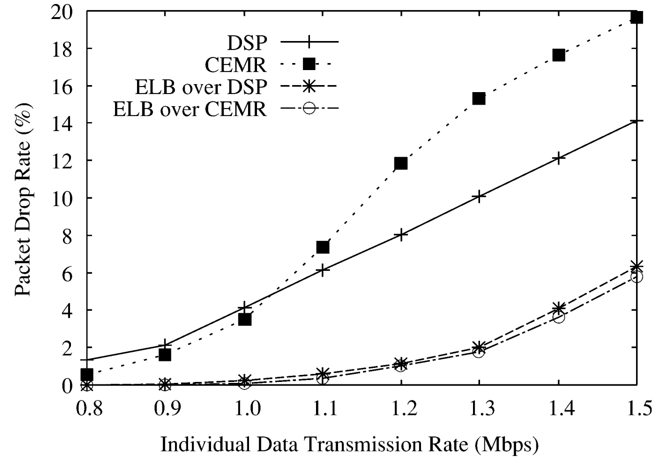

Fig. 2. Packet drops for different individual sending rates.

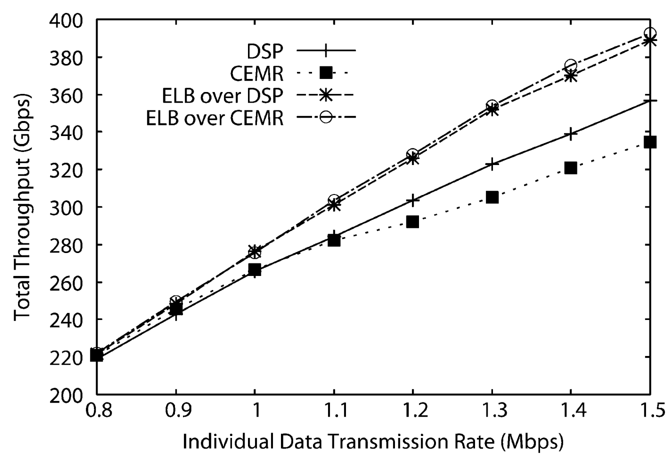

Fig. 3. Total throughput for different individual sending rates.

packet drops by alleviating congestion at satellites. The good performance of the ELB scheme in avoiding packet drops is also manifested in terms of the high throughput achieved by the ELB scheme. Fig. 3 shows that implementing ELB over CEMR and DSP leads to a remarkable increase in the total achieved throughput compared to the other two schemes, DSP and CEMR.

The ELB scheme also yields a more balanced distribution of traffic over the entire constellation. To illustrate the idea at hand, we plot the traffic distribution index for different values of sending rates in Fig. 4. The figure indicates that the implementation of ELB over DSP significantly outperforms the Dijkstra algorithm. This performance is attributable to the fact that the DSP algorithm bases its routing strategy on only finding paths with the shortest delay. Data is then transmitted over single paths during the entire transmission time. On the other hand, the ELB scheme searches for alternative paths when a satellite is about to get congested. Data is then transmitted over multiple less congested paths. This operation intuitively leads to a better and more efficient distribution of traffic among the constellation links. Compared to the CEMR scheme, while the implementation of ELB over CEMR exhibits a better distribution of traffic, the improvement is minimal. The underlying reason beneath this performance consists in the fact that CEMR also uses multiple

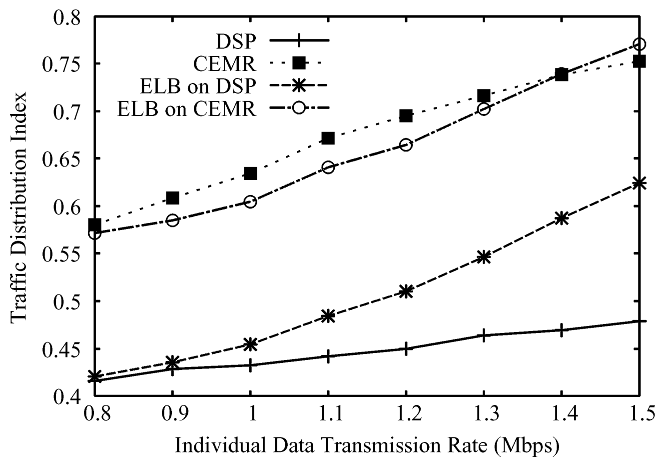

Fig. 4. Traffic distribution index for different individual sending rates.

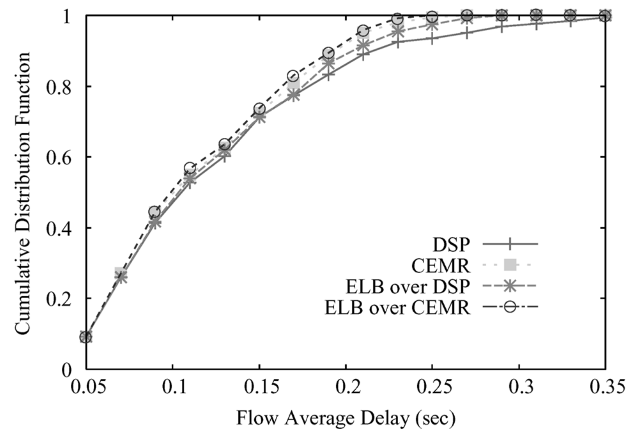

Fig. 5. Cumulative distribution function of flows' average delay (flows' transmission rate $= 1.0$ Mbps).

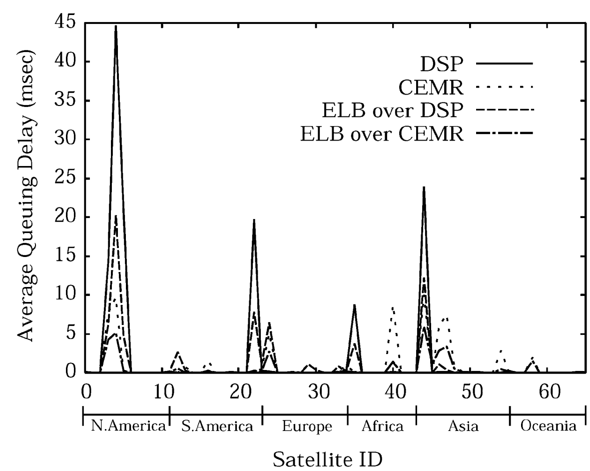

Fig. 6. Average queuing delay experienced at each satellite (flows' transmission rate $= 1.0$ Mbps).

disjoint paths for transmitting data. This fact makes different links involved in the transmission of data and hence yields a relatively wide distribution of traffic over the entire constellation.

In the ELB scheme, packets are sometimes forced to traverse more hops than in case of traditional routing algorithms. The ELB scheme may be thus thought of as a scheme that guarantees high throughput and low packet drops, but at the price of higher delays. However, considering the significant queuing delays that may result from congesting satellites, the additional hops that should be traversed by packets can be justified. Furthermore, it would be more beneficial for a system to have some packets experience some delay than having them completely discarded, mainly in light of the long time required for their retransmission in environments known for their long propagation delays.

To show the idea with more clarity, we plot the Cumulative Distribution Function (CDF) of the average delay of flows in Fig. 5. While the figure indicates the results in case of setting the sending rates of flows to 1 Mbps, identical plots were obtained in the case of other sending rates. The figure demonstrates that while some individual flows may experience longer delays than in case of traditional routing schemes, the aggregate performance of the ELB scheme in terms of delay is the best as the CDF plots of "ELB over DSP" and "ELB over CEMR" are higher than the plots of DSP and CEMR, respectively. As previously mentioned, the underlying reason beneath this performance consists in the abilities of ELB to alleviate congestion, to accordingly reduce the queue occupancies of satellites, and to ultimately reduce the queuing delays. To demonstrate this idea, we plot the average queuing delays (averaged over the simulation launch time) of each satellite in Fig. 6. Satellites covering populated and developed areas, such as North America, West Europe, and East Asia, exhibit the highest queuing delay as they have to route a high amount of traffic. In all cases, ELB outperforms all the other schemes as it reduces the average queuing delay.

2) Multiple Traffic Classes: To evaluate the performance of ELB in the presence of different traffic classes, we consider three traffic classes (A, B, and C) as previously explained. The total traffic is generated from the 600 non-persistent On-Off flows. The traffic percentages of traffic classes A, B, and C are set to 20%, 30%, and 50% ($\{a, b, c\} = \{0.2, 0.3, 0.5\}$), respectively as in [17]. The EWMA smoothing constant is set to 0.1. Under these conditions, the performance of the enhanced ELB (considering multiple traffic classes) is compared to that of the DSP algorithm and that of the traditional ELB (with no traffic classification). Both the enhanced ELB and the traditional ELB schemes are implemented over DSP.

Fig. 7 shows the average packet delay in case of the three schemes. In case of traditional ELB over DSP, the average delay is higher compared to that of DSP due to packet detouring. However, in case of enhanced ELB, delay of packets belonging to class A is smaller compared to that of other classes. This is because all packets of class A are sent through the default shortest path. When the traffic load is heavy, normal DSP exhibits the minimum average delay. However, this comes at the price of significant packet drops as earlier discussed. Fig. 8 shows the average normalized data throughput achieved by the three schemes. While traditional ELB outperforms DSP in terms of throughput, flows of class A achieves the highest throughput when the enhanced ELB is applied. In addition, throughput of class B is higher compared to that of class C due to detouring priority. These results demonstrate that with traffic classification, ELB can help both delay-sensitive and throughput-sensitive applications to meet their QoS requirements.

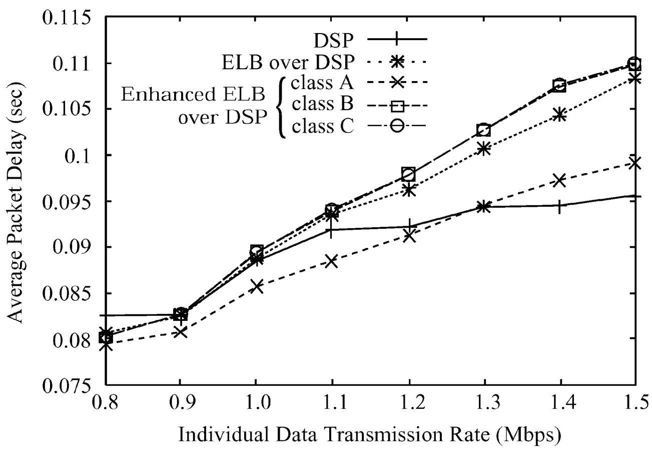

Fig. 7. Average packet delay for different individual sending rates.

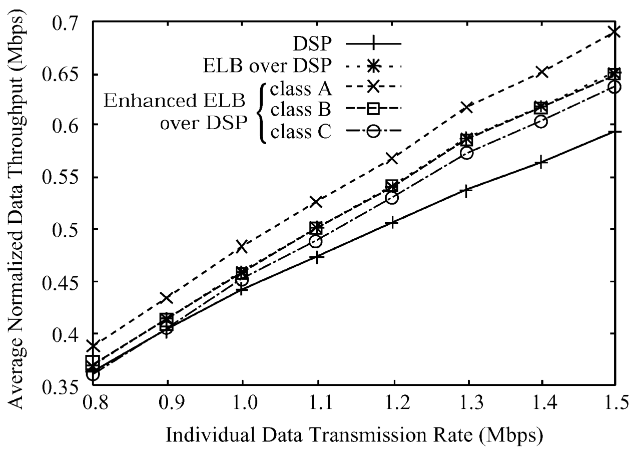

Fig. 8. Average normalized data throughput for different individual sending rates.

3) Packet Reordering Recovery: While different TCP connections can be simulated on the entire constellation, the behavior of our proposed packet-reordering recovery mechanism is best understood by considering a single TCP connection. We set one TCP connection whose minimal-hop is three over the United States region, the most congested area in the constellation. When the satellite in the middle of the main route gets congested (Fig. 9), a portion of the connection flow is forced (by the use of ELB) to change its path and traverse two more additional hops. In the implementation of the proposed packet-reordering recovery mechanism, the time-out interval to send back DupACKs in case of an out-of-order reception of packets is set to ($2L+10$ ms). This is equal to the propagation delay of two hops, which is the minimum extra delay when a packet is detoured, added to some minimal queuing delays roughly estimated at 10 ms. In [34], it is confirmed by simulations that TCP-PR outperforms most packet reordering solutions proposed in recent literature [31]–[33]. Standard TCP and TCP-PR are thus used as comparison terms. In the conducted simulations, parameters of TCP-PR are the same as in [34]. It should be recalled that in the original design of ELB, the setting of the traffic reduction ratio χ is instantly done as a function of the inbound and outbound traffic at a given satellite as in (7). To investigate the interaction of the three schemes in case of different values of

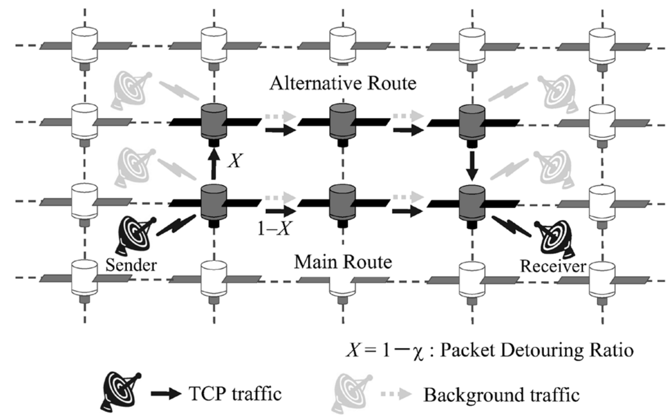

Fig. 9. A simplified simulation topology: a single TCP connection over the most congested area in the constellation (USA region).

χ, we plot the achieved goodput of the simulated TCP connection as a function of the packet detouring ratio $X (X = 1-\chi)$. We consider different satellite constellations by varying the ISL value (i.e., $d = 15$ ms, 20 ms, and 25 ms).

Fig. 10 shows the obtained results. The results demonstrate how the performance of standard TCP gets improved when adding our simple modifications to the receiver terminals. Indeed the proposed packet-reordering recovery mechanism exhibits higher goodput than standard TCP and that is in all the simulated scenarios. The reason beneath this good performance intuitively underlies behind the fact that in the proposed scheme DupACKs are not immediately sent back to the sender upon an out-of-order reception of packets and are rather hold for a time interval.

Compared with TCP-PR, the proposed packet reordering recovery mechanism shows much lower goodput in case of low values of X. However, the performance of TCP-PR degrades as X gets high values. In the vicinity of $(X = 0.8)$, the proposed scheme outperforms the TCP-PR as it achieves higher goodput. The good performance of the proposed scheme becomes more noticeable in constellations with high ISL values. The poor performance of TCP-PR in constellations with large ISL delays and high values of X is attributable to its contingency on an estimate of RTT and the bandwidth availability in the setting of its timer. For this reason, when ISL delay (d) is set to high values, errors take place in the estimation of timers, due in turn to errors in the RTT estimations made before and after the packet detouring operation. Similarly, when X takes large values, the available bandwidth in the alternative route becomes scarce and errors occur in the setting of timers.

Given the fact that today's Internet traffic is dominated by delay-nonsensitive traffic [29], and that in ELB, delay-nonsensitive (e.g., data and non real-time video) packets are first detoured upon an imminent congestion of a satellite, setting X to values larger than 0.8 should be practical. In this case, the value of the ISL delay, in other words, the constellation type will be the main factor in the decision of which scheme should be used to cope with the packet-reordering issue. Indeed, for MEO systems, the proposed packet reordering scheme is seen more suitable given its simplicity and its good performance in large-ISL constellations. In case of LEO systems with ISL delays smaller than 20 ms, TCP-PR can be used only if X is set to

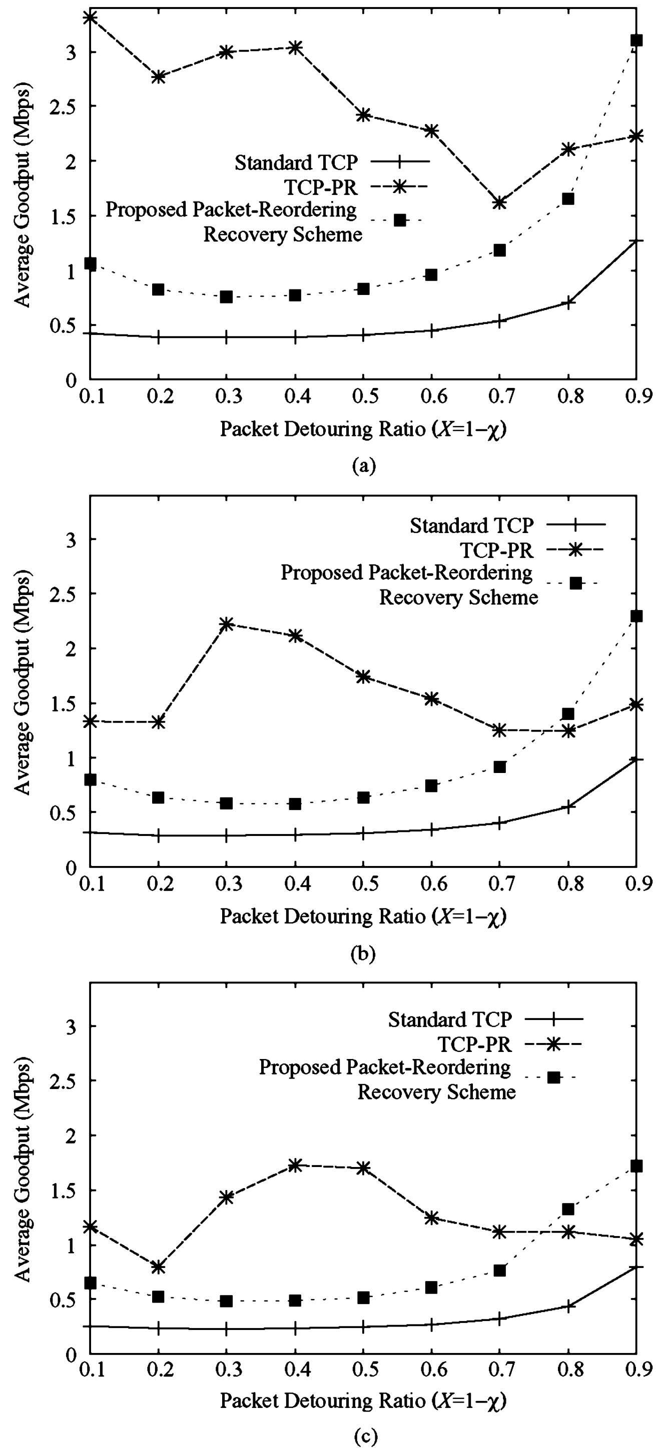

Fig. 10. Performance evaluation of the three schemes in terms of the achieved goodput for different ISL values. (a) ISL delay $= 15$ ms, (b) ISL delay $= 20$ ms, (c) ISL delay $= 25$ ms.

values smaller than 0.8. In this case, it should be guaranteed that the good performance of TCP-PR advocates for its complexity and its significant overhead in terms of both computation and memory at the sender side.

V. Conclusion

In this paper, we proposed a cooperative routing strategy that enables neighboring satellites to explicitly exchange information on their current congestion status. Satellites with queue occupancies exceeding a pre-determined threshold request their neighboring satellites to reduce their data forwarding rates. In response, the neighboring satellites transmit a predetermined portion of their data via less congested paths. The working of the proposed routing scheme is based on three metrics. A dynamic setting of these parameters is proposed based on easy-to-implement equations. The philosophy behind the parameters setting consists in reflecting the packet dropping probability in the parameters and guaranteeing a minimum level of stability for the satellites. To avoid the packet redistribution cascading issue, a routing cost metric, involving both the propagation delay and the queuing delay, is used. The targeted applications of the ELB scheme are preferably those that are delay insensitive and most importantly tolerant to a certain level of packet disorder or delay jitter. For this purpose, a class-based traffic detouring mechanism is added to the design of ELB. To cope with packet reordering issue in ELB and its impact on TCP, a TTL-based enhanced congestion control mechanism is also portrayed.

The proposed ELB scheme is practical and can be accomplished without changing the routing protocol in use. A set of simulations is conducted to evaluate the performance of the ELB scheme. Two implementations are considered; one over a recently proposed scheme, CEMR, and the other over the most widely used Dijkstra algorithm. The obtained simulation results elucidate the better performance of the ELB scheme in avoiding congestion, reducing queue lengths, lowering packet drops, and increasing the total throughput while maintaining a more balanced distribution of traffic over the constellation. The performance of the scheme is also evaluated in terms of delays. Interestingly, encouraging results are obtained. Indeed, while individual flows suffer from a slight increase in their delays as their packets have to traverse additional hops, the aggregate performance of the ELB scheme, seen in terms of the cumulative distribution function of flow average delays, is fairly good. This result is attributable to the abilities of the ELB scheme in reducing queuing delays. Furthermore, considering the extra time that may be required for retransmitting dropped packets in case of connection-oriented transport protocols, this result would be seen more promising.

Finally, it should be emphasized that the obtained results are critical for the implementation of Differentiated Services architectures over NGEO satellite constellations. The actual enhancements that the ELB scheme can indeed bring to such Diff-Serv-supporting NGEO satellite systems is an interesting area of research and forms the basis of our future research work.

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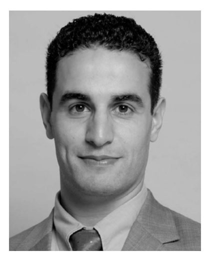

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