IP Traffic Load Distribution in NGEO Broadband Satellite Networks – (Invited Paper)

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Abstract. Given the fact that more than half of the world lacks a wired network infrastructure, satellite networks are seen as an important alternative to achieve global coverage. Since most of the world population lives around the equator or in middle-latitude regions, satellite constellations have to deal with different communication requirements from different regions. The traffic requirements become further unbalanced as the population density varies among urban and rural areas. This results in the congestion of some satellites while others remain underused. The issue of traffic engineering over satellite networks can be resolved by distributing the traffic in a balanced way over underutilized links. This paper proposes an Explicit Load Balancing (ELB) routing protocol which is based on information of traffic load at the next hop on the remainder of the path to the destination. A satellite with high traffic load sends signals to its neighboring satellites requesting them to decrease their sending rates before it gets congested and packets are ultimately dropped. Neighboring satellites should accordingly respond and search for other alternate paths that do not include the satellite in question. The performance of the proposed scheme is evaluated through simulations. From the simulation results, the proposed scheme achieves a more balanced distribution of traffic load, and reduces the number of packet drops and queuing delays. The resulting satellite constellation is a better-utilized and traffic-balanced network.

1 Introduction

Along with the rapid globalization of the telecommunications industry, the demand for Internet services is growing in terms of both the number of users and types of services to be supported. Along with this steady growth, provision of a plethora of wide-band Internet applications to metropolitan areas with a potentially large number of users, regardless of time and space limitations, is a challenging task for current terrestrial and wireless networks. Because of their extensive geographic reach and inherent multicast capabilities, satellite communication systems are seen as an attractive infrastructure to accommodate these high bit-rate services with diverse Quality of Service (QoS) requirements [1].

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Communications over satellites began successfully with the use of individual satellites in geostationary orbits. However, due to high signal delays caused by the high altitude of geostationary satellites, focus has been directed towards the development of new Non-Geostationary (NGEO) satellite communication systems called Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellite systems. NGEO systems promise to offer services with much lower latency and terminal power requirements than those offered by geostationary satellites. The design and development of these satellite networks have been thus the subject of extensive research in recent literature (e.g. Teledesic [2], Skybridge [3]).

NGEO satellite networks exhibit different characteristics from the traditional satellite or wired networks. The success of NGEO satellite networks in delivering high-speed access hinges on the ability of the underlying Internet protocols (IP) to function correctly and efficiently in NGEO satellite systems, systems characterized by rapidly time-varying network topologies [4]. The effect of such a communication environment on the working of IP protocols has been the focus of a large body of prior works [5]. Another important factor that the performance of IP protocols depend on in NGEO systems is related to routing. Indeed, whilst use of Inter-Satellite Links (ISLs) in multi-hops NGEO constellations provides more flexibility, it leads to complex dynamic routing [6]. 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 [7]. Support for IP routing within the satellite constellations is highly important for the implementation of Integrated or Differentiated Services (DiffServ) architectures to support QoS over satellite systems.

To route traffic over dynamic satellite constellations, several strategies have been proposed. Dynamic Virtual Topology Routing (DVTR) [8] and Virtual Node (VN) [9] 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 [10]. While most of these pioneering routing protocols search for the shortest path with the minimum cost, they do not take into account 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.

As a remedy to the above issue, this paper proposes an explicit routing protocol which is based on prior information of traffic load at the next hop. A satellite with high traffic load sends signals to its neighboring satellites requesting them to decrease their sending rates before it gets congested and packets are ultimately dropped. Neighboring satellites should accordingly respond and search for other alternate paths that do not include the satellite in question. This operation can be accomplished without changing the routing protocol in use. It can be easily implemented over any routing protocol, such as DVTR or VN routing schemes. The proposed concept targets only the packets of delay-insensitive applications. Delay sensitive applications are not subject to the proposed scheme and can be dealt with according to any traditional routing protocol. The proposed scheme is dubbed *Explicit Load Balancing (ELB).*

The remainder of this paper is structured as follows. Section 2 surveys the ongoing research efforts tailored to IP routing over NGEO satellite communication systems. Section 3 presents the key design philosophy behind the proposed scheme ELB. Section 4 portrays the simulation environment used to evaluate the performance of the proposed scheme and discusses the simulation results. The paper concludes in Section 5 with a summary recapping the significance of the research work elaborated in this paper.

2 Related Work

Current terrestrial Internet routing protocols, such as Open Shortest Path First (OSPF) [11] and Routing Information Protocol (RIP) [12], rely on exchanging topology information upon a change or set-up of a connection; that is in a connection-oriented manner. Applying such schemes to the rapidly and regularly-changing NGEO satellite network topologies incurs substantial overhead [13]. Several connectionless algorithms have been thus proposed to route data traffic over satellite constellations. They can be classified into two categories, namely constellation periodicity-based routing and onboard routing schemes.

Although satellite constellations experience frequent topological variations, these variations are highly periodic and predictable because of the strict orbital movements of the satellites. The basic idea behind protocols of the first category is to make use of this periodic and predictable nature of the constellation topology. Various schemes fall into this category. DVTR [8] and VN [9] protocols are the most worth-mentioning concepts.

In DVTR, the system period is divided into a set of time intervals. Over each interval, the topology remains constant. Link activation and deactivation are performed only at the beginning of intervals. Over each time interval, optimal shortest paths and alternate paths can be established using well-known methods such as the Dijkstra shortest-path algorithm. These routing tables can be then stored onboard and retrieved upon a change in the topology. One major credit of this operation consists in the removal of online computational complexity. However, this computation simplicity comes at the expense of large storage requirements, weak fault tolerance, and quasi-null adaptive capabilities.

In the VN scheme, virtual nodes (VNs) are assumed to be set in fixed positions relative to the surface of the Earth. A VN is embodied at any given time by a certain physical satellite, and a virtual network topology is set up with these VNs. The virtual topology is always embodied by the satellite constellation. When a satellite disappears over the horizon, its corresponding VN becomes represented by the next satellite passing overhead. The virtual topology remains accordingly unchanged. Each VN keeps state information, such as routing table entries or channel allocation information, pertaining to the users within its coverage area. Upon a satellite handoff, the state information is transferred from the first satellite to the second. Routing is performed in the instantaneous virtual topology using a common routing protocol. In such a manner, topology changes are hidden from routing protocols running on the constellation.

In the onboard routing mechanisms, as the name infers, routing tables are calculated onboard the satellites based on real-time information related to the network state. A potential number of onboard routings has been proposed in the recent literature. To mention a few examples, Henderson *et. al.* propose an onboard distributed routing protocol that selects the next hop based on minimization of the remaining geographic distance to the destination [14]. [15] proposes an onboard routing protocol specifically designed for multi-layered satellite constellations composed of LEO, MEO, and GEO satellites. In the proposed scheme, satellites in low layers (e.g. LEO) are grouped according to the footprint area of their corresponding satellites in the higher layers (e.g. MEO). This grouping is performed in each snapshot period. Higher satellites receive delay measurement reports from their group members in lower layers. Based on these reports, the higher-layer satellites compute the minimum-delay paths for their corresponding lower-layers members. While most of onboard routing schemes exhibit important adaptive capabilities, they impose significant challenges for the space devices in terms of the required computational and processing load. They ultimately question the scalability of their routing tables. Moreover, since these routing schemes focus on only finding paths with the shortest delays, they may turn unfavorable for the support of certain QoS requirements. They may be appropriate for only best-effort light-load traffic.

Given the important correlation between efficient routing strategies and the support of QoS, tremendous research efforts have been elaborated in recent years with respect to QoS over satellite constellations [16]. Most of these pioneering research works are based on the above-mentioned schemes. [10] provides a thorough discussion on the main merits and downfalls of these previous research works and indicates areas of possible improvements.

In the sphere of QoS over constellations with ISLs, the focus of earlier research work was on the integration of dynamic satellite networks with the Asynchronous Transfer Mode (ATM) [17][18]. Because of its provision of different levels of QoS guarantees and its concept of virtual path, ATM has been seen indeed as a promising solution for the provision of QoS over mobile satellites. However, the rapid growth of Internet-based applications motivates satellite operators to consider IP traffic as well. For IP-based satellite constellations, a number of interesting solutions has been proposed to provide QoS over satellites. In [19], Donner *et. al.* developed a Multi-Protocol Label Switching (MPLS) networking protocol for NGEO satellite constellations. The protocol is still in its infancy, and some important practical problems related to rerouting and maintenance overhead are still unsolved and deserve further study. On the other hand, [20] proposes a Traffic Class Dependent (TCD) routing algorithm. Different traffic classes are considered. The protocol differentiates between packets belonging to each traffic class and provides accordingly different levels of services. The

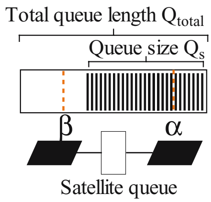
TCD protocol whilst attempts to guarantee QoS for different traffic classes, it may assign a single route for a specific class with huge traffic data and may ultimately result in heavily overloading the chosen path. This would intuitively affect the balancing of traffic load over the entire satellite constellation.

Another issue that is common among most conventional routing algorithms consists in the fact that 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, [21] 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 movements of satellites, such scenario may occur frequently. This would lead to the congestion of the chosen MFMR paths and ultimately unfavorable performance. In [22], 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 drawback 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 [23], 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 likeliness of packets to be dropped by the downstream hop either. To avoid packet drops and to more efficiently distribute traffic burden over multiple satellites, further study is needed to optimize the performance of the existing routing schemes. This challenging task underpins the research work outlined in the remainder of this paper.

3 Explicit Load Balancing Scheme

This section gives a detailed description of the proposed scheme, *Explicit Load Balancing (ELB)* scheme. First is an outline of the key components of multi-hop NGEO satellite constellations.

A multi-hop satellite constellation forms a mesh network topology. It is composed of N orbits and S satellites uniformly distributed over each orbit. The first and N^{th} orbits are neighbors in both sides due to the spherical shape of the Earth. Depending on the constellation type, each satellite is able to set up M ISLs with its neighboring satellites. Satellites along the counter-rotating seam



Queue ratio Q_r	Satellite State
$Q_r < \alpha$	Free
$\alpha \leq Q_r < \beta$	Fairly Busy
$\beta \leq Q_r$	Busy

Fig. 1. The three network states of satellites

have less neighboring satellites. There are two types of ISLs. Links between adjacent satellites in the same orbit are called Intra-plane ISLs, and links between neighboring satellites in adjoining orbits are called Inter-plane ISLs. Intra-plane ISLs are maintained permanently, but some Inter-plane ISLs may get temporarily deactivated when the viewing angle between two satellites is above a given threshold. In the remainder of this paper, we assume that each satellite is aware of the ISLs established with its neighboring satellites.

As previously discussed, while most traditional routing algorithms use different routing cost metrics to search for the most appropriate route, they do not take into account the congestion state of next hops on the remainder of the path to the destination. If the chosen next satellite is congested or about to be congested, the forwarded packets may either get discarded or experience a long queuing delay. To tackle this issue, neighboring satellites should mutually and dynamically exchange information on the states of their queues. In deed, at each satellite three representative states are defined based on the queue ratio[1] as shown in Fig. 1. The considered states are as follows:

– Free state: When the queue ratio (Q_r) is inferior to a predetermined threshold α ($Q_r < \alpha$), the satellite is considered to be in a free state.
– Fairly-busy state: Having the queue ratio between the threshold α and another predetermined threshold β ($\alpha \leq Q_r < \beta$), the satellite is considered to be in a fairly-busy state.
– Busy state: The satellite changes its state to busy when its queue ratio exceeds the threshold β ($\beta \leq Q_r$).

The choice of the thresholds α and β as queue ratios to indicate the congestion state of satellites is similar in spirit to the idea of major intelligent packet-discard policies such as Random Early Marking (REM) [24] and Random Early Discard (RED) [25].

Upon a change in the queue state of a given satellite, the latter broadcasts a *Self-State Advertisement (SSA)* packet to its M neighboring satellites informing them of the change occurrence. The SSA signaling packet carries information on the satellite ID and its state. It should be emphasized that SSA packets are broadcast to only the neighboring satellites and not over the entire connection path. Given their small size, overhead in terms of the bandwidth consumed by these signaling packets should not be an issue. When a satellite receives a

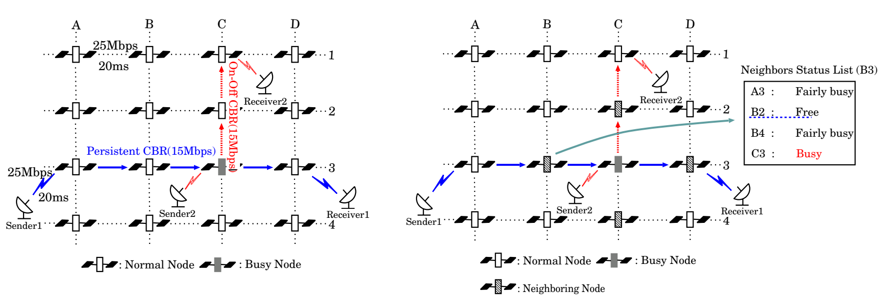
[1] The ratio of the queue size Q_s to the total queue length Q_{total} ($Q_r = \frac{Q_s \cdot 100}{Q_{total}}$).

SSA packet, it uses the enclosed information to update its *Neighbors Status List (NSL)*. Each NSL contains information on the current queue state of each neighboring satellite. When a satellite A experiences a state transition from free to fairly-busy state, it sends a warning message (via a SSA packet) 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 queue state of satellite A changes to busy, all neighboring satellites are then requested to forward (χ%) of traffic that has been transmitted via satellite A to other alternate paths. If the traffic includes different applications with different requirements, delay insensitive applications are to be first forwarded via the alternate paths. Packets of delay sensitive applications can be transmitted via satellite A if that would guarantee the delay requirements of the applications. It should be noted that the working of the proposed scheme can be accomplished without changing the routing protocol in use.

4 Performance Evaluation

Having described the details of the proposed scheme, focus is now directed on its performance evaluation. This section verifies how the proposed system is efficient in avoiding packet drops and enhancing the system throughput. The performance evaluation relies on computer simulation, using Network Simulator (NS) [26].

To better explain the mechanism of the proposed scheme, we consider the network topology example depicted in Fig. 2(a). The figure shows the case of the Iridium constellation where each satellite maintains ISLs with four other satellites ($M = 4$). All up-links, down-links, and ISL links are given a capacity equal to 25Mbps. Their delays are set to 20ms. In order to remove limitations due to small buffer sizes on the network congestion, buffers equal to the bandwidth-delay product of the bottleneck link are used [27]. Due mostly to its simplicity,



(a) Traffic concentration at satellite C3

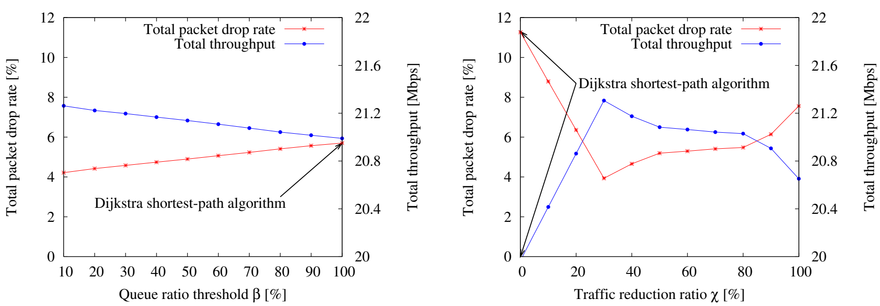
(b) Exchange of network state information among satellites

Fig. 2. An example showing the main operations of the ELB scheme

all satellites use Drop-Tail as their packet-discarding policy. The abstract configuration considers the case of two Constant Bit Rate (CBR) connections over two different routes, namely A3-D3 and C3-C1 (Fig. 2(a)). The sending rate of the two connections is set to 15Mbps. While the connection on the (A3-D3) route is simulated as a long-lived CBR flow, the traffic over the (C3-C1) route is modeled as a non-persistent On-Off connection. The On/Off periods of the connection are derived from a Pareto distributions with a shape equal to 1.2. The mean On period and the mean Off period are set to 200ms. The packet size is fixed to 1 kB. Simulations were all run for 20s, a duration long enough to ensure that the system has reached a consistent behavior. It should be noted that the above-mentioned parameters are chosen with no specific purpose in mind and do not change any of the fundamental observations about the simulation results. While the proposed scheme can be implemented over any routing protocol, in the performance evaluation, we consider the scenario of the proposed scheme over the Dijkstra's Shortest Path algorithm. The latter is used therefore as a comparison term.

Having all the traffic concentrated at satellite C3, this latter issues a SSA packet to its neighboring satellites (B3, C2, C4, and D3) indicating that its state has become "Busy". In response to the SSA packet, neighboring satellites set the state of C3 to Busy and update their NSL list accordingly. As satellite B2 is free, satellite B3 starts transmitting a portion of the (A3-D3) traffic via satellites B2, C2, D2, and finally the edge satellite D3 (Fig. 2(b)). This operation is continued until satellite C3 transits to a free state. By so doing, the overall network traffic becomes better distributed.

To investigate the effect of the threshold β on the system performance, we plot the total throughput and total packet drop rate experienced by the two connections for different values of β. α is set to half the value of β and the traffic reduction ratio χ is set to 70%. Fig. 3(a) shows the simulation results. The figure indicates that setting β to larger values leads to lower throughput and higher packet drops. Note that the case of ($\beta = 100\%$) refers to the use of



(a) Effects of β on the packet drops (χ = 70%)

(b) Effects of χ on the packet drops (β = 80%)

Fig. 3. Performance evaluation in terms of packet drops

only Dijkstra algorithm. The achieved performance is intuitively due to the fact that by setting β to high values, the proposed scheme would not have enough time to accommodate the traffic bursts and the queue ends up by discarding a high number of packets. This is ultimately translated into degraded throughput. In order to investigate the effect of the traffic reduction ratio χ on the system, we plot the total throughput and total packet drop rate experienced by the two connections for different values of χ in Fig. 3(b). We vary the value of χ from zero to 100%. While the case of ($\chi = 100\%$) refers to the extreme case when all packets are forwarded via other links, the case of ($\chi = 0\%$) refers to the case when the proposed scheme is not implemented and only the Dijkstra algorithm is in use. The queue ratio threshold β is set to 80%. From the figure, it can be deduced that the system exhibits its optimum performance when the value of χ is set to 30%. This result is attributable to the fact that smaller values of χ put most of the traffic burden on satellite C3, whereas higher values of χ congest satellite C2. Both scenarios lead to higher packet drop rates and degraded throughput. Setting χ to optimum values helps also to avoid the re-distribution cascading issue that may occur to the already-distirubted portion of traffic. While this result is promising, it should be observed that it comes at the price of higher delays. In deed, packets have to traverse more hops than in case of traditional routing algorithms. For delay insensitive applications, this should not be an issue. For delay sensitive applications, a tradeoff between the number of packet drops and the parameters β and χ should be established. This forms the basis of our future research work.

5 Conclusion

In this paper, we proposed an Explicit Load Balancing routing protocol to efficiently distribute traffic over multi-hop NGEO satellite constellations. The key idea behind the proposed scheme is to reduce the sending rate of data traffic to nodes that are about to be congested and use instead nodes that are in free states. For this purpose, the proposed scheme uses information of traffic load at the next hop on the remainder of the path to the destination. This information is exchanged among neighboring satellites via signaling packets. The efficiency of the proposed scheme in distributing traffic data and accordingly avoiding packet drops is investigated through simulation using a simple satellite topology. While the setting of the scheme parameters (β & χ) deserve further study and investigation, the simulation results obtained so far are encouraging. In the performance evaluation, the authors considered the case of a small part of the Iridium constellation, as future research works, they are currently working on the performance evaluation of the scheme over the entire satellite constellation.

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