Improving ELB in Multi-Hop Satellite Constellations with Short ISL Delays

Tetsuya Takahashi[*†], Tarik Taleb[‡†], Kazuo Hashimoto[§†], and Nei Kato[§†]

Graduate School of Information Sciences, Tohoku University, Sendai, Japan

The community of next generation multi-hop satellite networks users will exhibit high variance in geographical distributions. In this regard, efficient traffic control and load balancing schemes are mandatory.

Recently the authors have proposed an efficient method for load balancing over multi-hop satellite networks dubbed an "Explicit Load Balancing" (ELB). In ELB, each satellite monitors its own queue length. If a satellite is about to get congested, it sends an explicit message asking its neighboring satellites to detour a portion of their traffic to alternative paths that do not involve the congesting satellite. Simulation results demonstrated the efficiency of ELB in satellite networks with relatively long inter-satellite link (ISL) delays. In case of satellite constellations with shorter ISL delays, the working of ELB becomes limited as the neighboring satellites are more likely to get promptly congested due to the short detouring range.

To cope with this limitation, there is need for explicit exchange of the congestion state among not only neighboring satellites but also satellites at k-hop distance from the congesting satellite. The key idea of the proposed enhancements to ELB consists in the use of the Gaussian distribution to determine the parameter k and the cost of links among satellites that are k-hop distant from the congesting satellite. The performance of the proposed enhancements is evaluated through simulations. The simulation results elucidate that the proposed solution improves the performance of ELB, especially in satellite constellations with short ISL delays.

I. Introduction

Next generation multi-hop satellite networks such as Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) are expected to provide global wireless Internet services. They can provide data with short delay and low power requirement at end-terminals. This is why these networks are seen highly attractive. But almost all the users connect to the constellations from land, however the surface area of the land is less than 30% of the whole earth surface. The variance of land mass is also significantly high due to the geographical distribution. Consequently, satellites which cover urban areas are likely to be congested while the network resources are limited. Furthermore, the on-going exponential growth of the number of users of Internet services makes this problem more significant.

Recently, the authors have proposed a novel method for solving this problem called "Explicit Load Balancing" (ELB).[1] In ELB, each satellite detects its congestion by monitoring its own queue length. Based on the change of queue length, two thresholds are defined and used for traffic load balancing. If the queue length of a satellite exceeds the thresholds, that satellite advertises its state, for example "busy" or "fairly-busy" states, to its neighboring satellites. Satellites which received the explicit message start detouring their traffic in order to mitigate the congestion.

[*]Master Cource Student

[†]Graduate School of Information Sciences, Tohoku University, Aoba 05, Aramaki, Aoba-ku Sendai, 980-8579 Japan, Non-member

[‡]Assistant Professor

[§]Professor

Multi-hop satellite constellations with short inter-satellite link (ISL) delays have short footprints. Consequently, such constellations require a large number of satellites to cover a certain area. Hence, these constellations are often prone to congestion. For example, Iridium has 66 active satellites and the radius of its footprint is about 2,200 km. A single Iridium satellite alone can cover Japan, Korea and Eastern China. But in Teledesic which has 288 satellites, two or three satellites are needed to cover the East Asian region. It indicates that satellite constellations with short ISL delays tend to have a series of "busy" nodes.

In the previous version of ELB, messages about traffic load are exchanged between only neighboring satellites. Therefore, the detouring efficiency is likely to be limited. To cope with this limitation, a wider message exchange is needed, i.e., the explicit messages of the congestion state must be exchanged among not only neighboring satellites but also satellites at k-hop distance from the congesting satellite where $k \geq 1$. The key idea of this solution is based on Gaussian distribution, which is used to calculate the detouring rates and the link costs. The simulation is performed using NeLS satellite constellations. Simulation results indicate better traffic balancing compared with the original ELB scheme.

The remainder of this paper is organized as follows. Section II explains the previous version of ELB and also presents its problem. Section III introduces the algorithm of the extended ELB. The performance of the proposed method is evaluated in section IV. Finally, section V concludes the paper.

II. Related Work

Several routing protocols for Non-Geostationary satellite (NGEO) constellations have been studied by many researchers in order to adapt routing protocols to these dynamic satellite networks. Dynamic Virtual Topology Routing (DVTR)[2] and Virtual Node (VN)[3] are the best known concepts. Based on these schemes, various investigations have been carried out in the recent years. However, the main objective of these approaches is to find the path with shortest end-to-end delay without paying much attention to other Quality of Service (QoS) parameters.

To follow these limitations, some routing protocols with consideration of QoS have been developed. Minimum Flow Maximum Residual (MFMR)[4] and Compact Explicit Multi-path Routing (CEMR)[5] use quantitative indices such as the number of flows and queuing delays in calculating optimal path, respectively. However, they still have some room for improvement. Therefore, a more effective scheme called ELB has been proposed. In ELB, each satellite exchanges realistic congestion information and traffic detouring is executed depending on the condition of the traffic load.

In the previous version of ELB,[1] every satellite monitors its queue length and accordingly adjusts two thresholds, α and β. Let Q_r be the ratio of a current queue occupancy to the size of the queue of a satellite. The relationship between α and β is expressed by:

$$0 \leq \alpha \leq \beta \leq 1 \; . \tag{1}$$

A satellite is considered to be in a Free State (FS) when ($Q_r \leq \alpha$), and the state when Q_r is in between α and β is called a Fairly Busy State (FBS). The satellite is considered to be in a Busy State (BS) if ($Q_r \geq \beta$). If a state of a satellite becomes FBS, it sends explicit messages to its neighboring satellites indicating it is about to get congested. The neighboring satellites calculate an alternative path which does not include the source satellite of the messages. If the incoming traffic to the soon-to-be-congested satellite still does not decrease, Q_r will exceed the threshold β. At this point, the congested satellite sends Busy State Advertisements (BSAs) to its neighboring satellites, and they start packet detouring process. BSA includes the ID of the congested satellite and the Traffic Reduction Ratio (TRR), χ. After receiving BSA, the neighboring satellites detour packets according to χ.

Thresholds α and β are calculated on the basis of packet dropping probability. Let I and O denote the total input and output traffic rates at a given satellite, respectively. Let Q_l and $q(t)$ be its total queue length and its queue occupancy at time t, respectively. The elapsed time, δ_d, until a packet drop occurs can be predicted as follows.

$$\delta_d = \frac{(Q_l - q(t)) \cdot P_{avg}}{I - O} \tag{2}$$

where P_{avg} is the average packet size at a given queue, I and O are assumed constants over a short period of time. Finally, the packet dropping probability can be expressed by using δ_d as following.

$$p = \min\left(1, \frac{\delta + d}{\delta_d}\right) \tag{3}$$

where δ is time interval and d is the propagation delay of ISL. After deriving p, the thresholds α and β are defined by:

$$\beta = 1 - p \tag{4}$$

$$\alpha = \frac{\beta}{2} \ . \tag{5}$$

The value of the TRR parameter determines whether ELB can provide good performance or not. The TRR value must not be excessively large because the most important thing in its calculation is to prevent new congestion by detouring traffic. Therefore, the algorithm of calculating TRR has been designed in such a way that the congested satellite can recover from BS within at least a period of time θ. Let I_t and I_s denote the total rates of traffic coming from terminals within the coverage area of a satellite and the neighboring satellites, respectively. When the satellite enters BS, it requests its neighboring satellites to reduce their sending rates. At the time of sending the requests, the queue occupancy of the congested satellite when these requests arrive at them can be calculated as follows.

$$q(t_{BSA}) = \min\left(Q_l \cdot \beta + \frac{d \cdot (I_s + I_t - O)}{P_{avg}}, Q_l\right) \ . \tag{6}$$

To achieve the recovery from BS, taking at least time θ, the new rate of traffic coming from neighboring satellites, I_s^{new}, should satisfy the Equation (7) and the value of TRR can be computed as expressed in Equation (8).

$$(I_s^{new} + I_t) - O = \frac{P_{avg} \cdot (q(t_{BSA}) - Q_l \cdot \alpha)}{\theta} \tag{7}$$

$$\chi = \min\left(\max(0, \frac{I_s^{new}}{I_s}), 1\right) \ . \tag{8}$$

The neighboring satellites send packets to the congested satellite at the ratio of χ, and $[(1 - \chi) \times 100\ \%]$ of packets are detoured by the neighboring satellite.

In this paper, the proposed method extends the original ELB algorithm by employing Gaussian distribution. This approach can increase the efficiency of ELB, and the risks of packet drops are decreased, which is explained in the next section.

III. Operational Overview of the Proposed Method

III.A. Introduction of the Gaussian Distribution

As mentioned earlier, the explicit messages which indicate the satellite state should be exchanged between not only neighboring satellites but also satellites at k-hop distance from the congested satellite in satellite constellations with short ISL delays. We designed the proposed method based on the following conditions.

- BSAs must reach satellites at k-hop distance from congesting satellites and all satellites which received these BSAs must start the detouring process.
- As the distance from the congested satellite increases, the value of the TRR parameter should be decreased gradually because the probability of passing over the congested satellite also decreases.
- The explicit messages should not be sent to the whole of the satellite constellation due to their overheads.

To satisfy the above conditions, we tried applying the property of Gaussian distribution to extend ELB. Gaussian distributions are used for computing link costs of detoured packets and also the value of the TRR parameter.

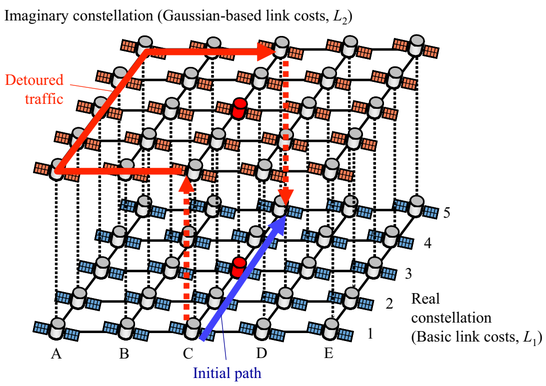

Figure 1. A real constellation and an imaginary constellation.

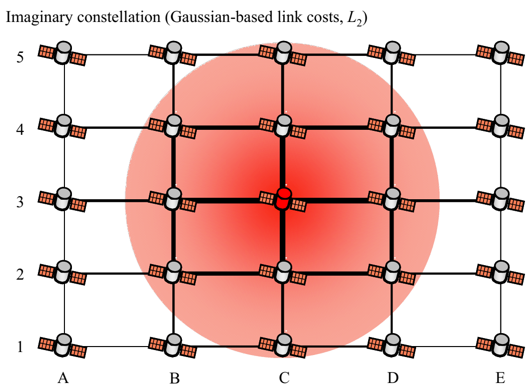

Figure 2. Gaussian-based link costs in the imaginary constellation.

III.B. Application of the Gaussian Distribution in Extended ELB

The proposed method uses realistic distances between satellites. Each distance can be computed without exchanging packets due to the regularity of the constellation. Therefore, overheads do not occur in using distance information. In order to inform satellites of congestion information, BSAs are sent to the satellites within a certain distance, D_{BSA} from the congested satellite, which means that the satellites lying beyond this distance (D_{BSA}) are not aware of that congestion information. Each satellite has a list B of congested satellites based on received BSAs. If a satellite finds its B to be empty, it realizes that there is no congested satellite in its neighborhood, and sets the TRR value to zero. But if there are some congested satellites in B, the satellite i, which has the list, enters in detouring mode and its TRR value χ_i is computed as follows.

$$\chi_i = \chi_j \cdot \exp\left(-\frac{D_{i,j}^2}{2\sigma^2}\right) \tag{9}$$

where σ and $D_{i,j}$ denote the variance and the realistic distance between satellite i and j, respectively. The value of j is determined as follows.

$$j = \min_{s \in B} D_{i,s} \tag{10}$$

In the proposed method, the basic link cost between satellites i and j in a satellite constellation, $L_{1,(i,j)}$, can be defined based on the routing protocol used in that constellation. However, at the satellite in detouring mode, the $(1-\chi)$ portion of traffic data will be transmitted based on Gaussian-based link cost, $L_{2,(i,j)}$, which is defined as shown in Equation (11).

$$L_{2,(i,j)} = \rho_{i,j} \cdot L_{1,(i,j)} \tag{11}$$

where $\rho_{i,j}$ is defined as follows.

$$\rho_{i,j} = 1 + \xi_{i,j} \tag{12}$$

$$\xi_{i,j} = \begin{cases} 0 & (\text{if } B = \phi) \\ \max\limits_{s \in B} \dfrac{M}{\sqrt{2\pi}\sigma} \left[\max\left(\exp(-\dfrac{D_{i,s}^2}{2\sigma^2}), \exp(-\dfrac{D_{j,s}^2}{2\sigma^2}) \right) \right] & (\text{if } B \neq \phi) \end{cases} \tag{13}$$

The objective of Equations (9) and (13), which are based on Gaussian distribution, is to spread traffic near congested satellites widely. The idea of this scheme can be interpreted by dividing a satellite constellation into a two-layered constellation as shown in Fig. 1. Considering the example scenario in Fig. 1, the traffic from satellite C1 to satellite C5 should be transfered along the blue arrow (C1-C2-C3-C4-C5) based on Dijkstra's Shortest Path (DSP) routing. However, if the congestion occurs at satellite C3, BSAs are sent to the satellites in the neighborhood and the $(1-\chi)$ portion of traffic is transfered over the imaginary constellation whose link costs are computed by Equation (11). Fig. 2 indicates the use of Gaussian-based link costs. The satellites in the circle, whose radius is D_{BSA}, are in detouring mode, and the costs of all the links inside or partially inside the circle are increased based on Equation (11). The widths of the links in Fig. 2 are approximately proportional to the link costs.

In addition, the radius of area where a congested satellite sends BSA packets, D_{BSA}, should be more than 3σ because about 99.7% values drawn from a Gaussian distribution are within 3σ.

IV. Performance Evaluation

IV.A. Simulation Setup

In this section, we compare the performance of the proposed method to that of the original ELB scheme by using the Network Simulator version 2 (NS-2).[6] We have evaluated ELB considering Iridium constellation.[1] However the objective of this paper is to evaluate the proposed method over satellite constellations with short ISL delays. Consequently, we consider NeLS system which is a constellation proposed by National Institute of Information and Communications Technology (NICT), Japan. NeLS system has 120 satellites compared to 66 satellites with the Iridium constellation. Features of NeLS system are indicated in Table 1. Uplinks, downlinks and ISLs are each given a capacity of 25 Mbps (C = 25 [Mbps]). Their delays are computed based on the features of Table 1. In our setup, the propagation delays of intra-orbit satellite links are about 13 msec and those of inter-orbit satellite links are around 7 msec. The average packet size is set to 1 kB (P_{avg} = 1 [kB]). The queue is based on Drop-Tail, and queue length, Q_l is set to 200 packets. Concerning the parameters of the Gaussian distribution, σ and M are set to 4000 km and $20\sqrt{2\pi}\sigma$, respectively. The radius of exchanging BSAs is fixed to 4σ ($D_{BSA} = 4\sigma$).

For traffic generation, we consider 500 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. Both the average burst time and the average idle time are set to 200 msec. The source and destination end-terminals are dispersed all over the Earth. 394 of 1,000 terminals are deployed according to the distribution of the 30 largest urban agglomerations ranked by population size of 2005[7] in the rate of a terminal per one million people. The other terminals are deployed randomly over the Earth. Source terminals send data at constant rates from within the range of 0.8 Mbps to 1.2 Mbps.

To evaluate the efficiency of extending the advertisement area, the parameters of the original ELB and that of the proposed method are set to the same values. In the performance evaluation, we use the Dijkstra's Shortest Path (DSP) algorithm and basic link costs are proportional to their propagation delays. The intervals of checking queue state and updating routing table are both 50 msec. Simulations are all run for 10 seconds and the desired time for a satellite to reside in the Free State after a transition to the Busy State is set to 200 msec ($\theta = 200$ [msec]).

Table 1. Features of NeLS satellite system

Number of Satellites	120
Planes	10
Satellites per plane	12
Altitude	1200 km
Inclination	55 deg
Eccentricity	0
ISLs per satellite	4
Elevation Angle	20 deg

IV.B. Simulation Results

First, we evaluate the performance of the proposed method in terms of the total packet drop rate experienced by the simulated 500 connections during 10 seconds. Fig. 3 indicates that the proposed method achieves lower drop rate compared to the other routing algorithms. The proposed method works more efficiently, particularly when the individual data transmission rate increases. The reason of this improvement can be explained by the graph in Fig. 4. This figure shows the traffic distribution index, f.

$$f = \frac{(\sum_{k=1}^{N} n_k)^2}{N \sum_{k=1}^{N} n_k^2} \tag{14}$$

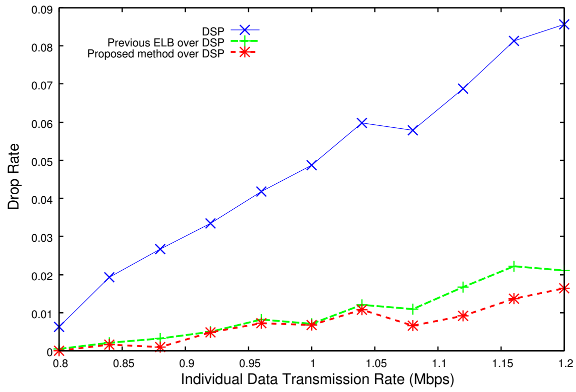

Figure 3. Packet drop rate for different individual sending rates.

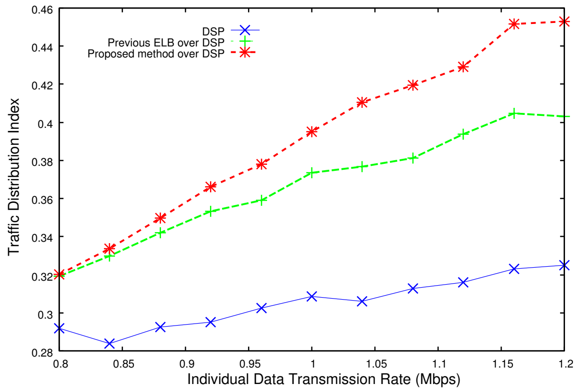

Figure 4. Traffic distribution index for different individual sending rates.

where N is the number of ISLs and n_k denotes the actual number of packets that traverse through the k^{th} ISL. This index ranges from zero to one and indicates how well the traffic is distributed over the satellite constellation. As shown in Fig. 4, the proposed method achieves a significant improvement over both DSP and the previous version of ELB over DSP, in terms of the traffic distribution. For low sending rates, both ELB and the proposed scheme obtained similar traffic distributions. For example, when the individual data transmission rate was 0.8, the values of f for ELB and extended ELB were close, 0.319 and 0.320, respectively. The DSP method performed rather poorly, with $f = 0.292$. The proposed method showed better performance in terms of traffic distribution as the sending rate increased. This became significant from sending rate of 0.92 and above. For sending rate of 0.96 Mbps, the values of f for ELB and the proposed method were 0.359 and 0.378, respectively. The highest value of f (0.453) was encountered at the highest sending rate, 1.2 Mbps, in case of the proposed method. On the other hand, the f-values of ELB and DSP for the same sending rate were only 0.403 and 0.325, respectively. This result indicates that the limited network resource is used more efficiency in the proposed scheme than that in the other approaches.

V. Conclusion

In this paper, we improved a routing strategy called Explicit Load Balancing (ELB) based on Gaussian distribution for next generation multi-hop satellite constellations with short inter-satellite link (ISL) delays. The difference between the original ELB and the proposed method is the range of exchanging information about current congestion state. In constrast with the previous version of ELB, Busy State Advertisements (BSAs) are exchanged among satellites at more than one-hop distance from the congested satellite. Compared with DSP and the original ELB, the proposed scheme yields lower drop rate and a more efficient traffic distribution, verified by simulation results.

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