

Analysis of Priority-based Adaptive Routing in Satellite Networks

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Abstract — In this paper we analyze a priority-based shortest path routing approach for mesh-like modeled satellite constellations. In a mesh-like satellite network, there are many shortest paths between a source-destination ($s-d$) pair in terms of hop-count. Therefore, deciding on the best shortest path becomes a crucial task for utilizing the network resources. In [1], we introduced a Priority-based Adaptive Routing (PAR) scheme that accounts for utilization metric of Inter Satellite Links (ISLs). Moreover, to avoid needless splitting of a flow and achieve better utilization of ISLs, enhanced PAR (ePAR) scheme is proposed. However, there are a number of ePAR parameters that should be adjusted depending on the network and traffic characteristics. In this paper, we provide a detailed analysis of ePAR scheme to form an opinion on the parameters setting.

Index Terms— satellite networks, adaptive routing, priority mechanism

I. INTRODUCTION

Satellites are expected to widely appear in future telecommunication systems, due to their extensive geographic reach, inherent multicast capabilities, etc. Researches on multiple fronts have been under investigation for improving both the performance and capability of satellite networks. These researches include but not limited to integration of satellite and terrestrial networks, integrated satellite architectures, stand alone satellite systems, beam scheduling, on board signal regeneration, adaptive modulation and coding, multiple access, flow control, resource allocation, and other service and system specific attributes. In this paper, we consider developing an efficient routing algorithm for achieving increased throughput, decreased delay and maintain Quality of Service (QoS) in satellite networks.

There are several routing algorithms proposed for Low Earth Orbit (LEO) satellite constellations. [2] deals with adaptive routing with a limited set of alternative routes. However, there may be many shortest paths in a mesh-like network which can be fully utilized. [3]

proposes a Datagram Routing Protocol, where Inter Satellite Link (ISL)'s are considered to have variable length and each satellite decides on the neighboring satellite to find the shortest delay path. In this approach, a satellite may change its decision in case of excessive queue length; however it is desired to avoid congestion before it happens. [4] proposes a Maximum-Flow Minimum-Residual routing algorithm which depends on the traffic load. Main drawback of this algorithm is that a prior knowledge of the flows in the network is needed and it does not consider dynamic changes in the traffic flow. [5] proposes an Adaptive Flow Deviation algorithm which is also not suitable for the dynamic traffic which could be caused due to inherent nature of Internet traffic, movement of satellites, and differentiation of day and night usage, etc. In [1] we propose a novel priority-based adaptive shortest path routing technique (PAR) that distributedly sets the shortest path through a destination and which is more suitable for dynamic traffic. Further we make an enhancement on PAR for better utilization of ISL's and propose ePAR. Relying on simulation results we show that the proposed techniques not only increase throughput, but also decrease delay. In this paper, we make an analysis of ePAR. Since there are number of parameters that should be adjusted properly, our analysis provides an opinion on the setting of these parameters. In Section II, we present the background about the proposed algorithms. In Section III, we provide the analysis of ePAR. In Section IV, we conclude this work.

II. BACKGROUND

In a mesh-like satellite network, there are many shortest paths between a source-destination ($s-d$) pair in terms of hop-count. At each satellite node, more than one outgoing link could be on one of the shortest paths. Decision on sending the data from which of those links has an important effect on the distribution of the traffic and utilization of ISLs. In [1], we propose a Priority-based Adaptive Routing Algorithm (PAR), in which direction decision is made at each hop by a priority mechanism, depending on the past utilization and buffering information about the links. Determination of

the priority metric is a critical issue that effects the performance of PAR. One possibility is to use the following metric:

$$\mu = n_a \quad (1)$$

where n_a is the number of packets that arrive to the link. However, the congestion in a link is not only related with the number of arrivals to it. For example among the links with same number of arrivals, the link with shorter queue length may be favored. Therefore in [1], the following priority metric is proposed:

$$\mu = \alpha \cdot u_r + \beta \cdot l_q + \delta \cdot n_d \quad (2)$$

where u_r is the utilization ratio of the link, l_q is the average queue length, and n_d is the dropped data per second. Using this metric, traffic tends to distribute the links in a more balanced way. Similarly, Equation 2 can be changed as:

$$\mu = \alpha \cdot n_t + \beta \cdot l_q + \delta \cdot n_d \quad (3)$$

where n_t is the successfully transmitted data per second in the corresponding link. Note that, α , β and δ are design parameters that should be adjusted properly due to the traffic requirements and network topology.

It is important to note that most of the contentions occur between packets with different source-destination ($s-d$) pairs. Therefore it would be better to switch packets with same $s-d$ pairs to the same outgoing link. This suggests that the performance of PAR algorithm may be enhanced by using the following metric:

$$\mu_{sd} = \alpha \cdot (n_t - n_t^{sd}) + \beta \cdot l_q + \delta \cdot n_d \quad (4)$$

where n_t^{sd} is the amount of transmitted packets corresponding to $s-d$ route, and μ_{sd} is the priority metric for traffic traversing on $s-d$ route. At the expense of increased complexity on satellite nodes, better ISL utilization may be achieved in this technique, which we called enhanced PAR (ePAR). In this work, for the sake of simplicity, we assume that buffers are sufficiently large, hence we ignore n_d .

$$\mu_{sd} = \alpha \cdot (n_t - n_t^{sd}) + \beta \cdot l_q \quad (5)$$

Defining a new variable $n_{sd} = n_t - n_t^{sd}$, Equation 5 can be further reduced to:

$$\mu_{sd} = \alpha \cdot n_{sd} + \beta \cdot l_q \quad (6)$$

Considering that the latest utilization and buffering information is more important than the older ones, an aging mechanism is needed to be utilized while computing the priority metric. One possibility is to take the average of last t seconds. However this mechanism has some drawbacks. Firstly, the information belonging to earlier times has also an importance, and completely ignoring them is not reasonable. Moreover, storing the information about last t seconds involves high space complexity. In [1], an aging mechanism is proposed as follows: We define an aging period with length t_a . At the beginning of each period, we store the current μ value in a variable called μ^o . Then satellite starts to collect utilization and buffering information in a new variable called μ^n . At t_0 'th time unit of a given period, μ is calculated as follows:

$$\mu = \mu^o \cdot \left(1 - \frac{t_0}{2t_a}\right) + \mu^n \cdot \left(\frac{t_0}{2t_a}\right) \quad (7)$$

Equation (7) is for PAR. For ePAR, it can be rewritten as:

$$\mu_{sd} = \mu_{sd}^o \cdot \left(1 - \frac{t_0}{2t_a}\right) + \mu_{sd}^n \cdot \left(\frac{t_0}{2t_a}\right) \quad (8)$$

This implies that, n_{sd} and l_q can be calculated in same manner:

$$n_{sd} = n_{sd}^o \cdot \left(1 - \frac{t_0}{2t_a}\right) + n_{sd}^n \cdot \left(\frac{t_0}{2t_a}\right) \quad (9)$$

$$l_q = l_q^o \cdot \left(1 - \frac{t_0}{2t_a}\right) + l_q^n \cdot \left(\frac{t_0}{2t_a}\right) \quad (10)$$

In the rest of the paper we make an analysis of the ePAR algorithm, utilizing the mentioned aging mechanism.

III. ANALYSIS

Consider that α , β and δ in Equation 4 denotes the design parameters that should be adjusted properly depending on the network characteristics. By the optimal selection of these parameters, not only better load distribution can be achieved, but also traffic flows can be made more stable. By stability, we mean avoiding the needless fluctuations due to redirection of all the flows in a congested link, simultaneously. In this section, we aim to form an opinion about how to set these parameters to achieve more stable systems.

Suppose a satellite network in which arrival rate of an $s-d$ flow is Poisson distributed with mean $1/\lambda$ bps. We represent a flow with source x , and destination y with f_{xy} . We consider a scenario, where a new flow is participated to a link that is already utilized just below its capacity, and the data arrival rate exceeds its capacity by the participation of the new flow.

We assume that the existing aggregate flow (F_e) in a particular link has a rate of X/λ bps. A new flow (f_{sd}) with rate r_{sd}/λ is participated to the corresponding link. After the aggregation of the existing flow F_e , and the new flow f_{sd} , the total arriving flow becomes $(X + r_{sd})/\lambda$. Supposing that this value is greater than the link bandwidth, B/λ , total amount of traffic to serve is B/λ and total flow to be blocked per second is $(X + r_{sd} - B)/\lambda$. Assuming that the blocking probability for each flow is same, blocked portion of F_e will be:

$$b_F = (X + r_{sd} - B) \cdot \frac{1}{\lambda} \cdot \left(\frac{X}{X + r_{sd}}\right) \quad (11)$$

And the transmitted portion of F_e will be:

$$t_F = \frac{B}{\lambda} \cdot \left(\frac{X}{X + r_{sd}}\right) \quad (12)$$

Since t_F is the total transmitted data per second,

except the portion corresponding to s - d traffic, it is the new value that n_{sd} will converge. We represent this value as ψ_{sd} .

$$\psi_{sd} = \frac{B}{\lambda} \cdot \left(\frac{X}{X + r_{sd}} \right) \quad (13)$$

Before the participation to the corresponding link, n_{sd} was equal to the total transmitted data in the link, since n_i^{sd} was zero. We represent the old value of n_{sd} with ψ_{sd}^o :

$$\psi_{sd}^o = \frac{X}{\lambda} \quad (14)$$

For any other flow f_{ij} that uses the same link (and hence that is a part of F_e):

$$\psi_{ij} = \frac{B}{\lambda} \cdot \left(\frac{X + r_{sd} - r_{ij}}{X + r_{sd}} \right) \quad (15)$$

where ψ_{ij} is the new value that n_{ij} will converge. The initial value for n_{ij} is determined by the difference between total initial flow and the flow with source i and destination j :

$$\psi_{ij}^o = \frac{X - r_{ij}}{\lambda} \quad (16)$$

Amount of blocked data continuously increases as time passes, and t seconds after the participation of the new flow, length of queue becomes $t \cdot \frac{X + r_{sd} - B}{\lambda}$, assuming that the buffer is initially empty. Since we assume increment in queue length is linear, average queue length between time t_1 and t_2 is:

$$\frac{t_1 + t_2}{2} \cdot \frac{X + r_{sd} - B}{\lambda}$$

For clear illustration, we represent increment in the queue length (per second) with a new variable ξ :

$$\xi = \frac{X + r_{sd} - B}{\lambda} \quad (17)$$

Table 1 shows how n_{sd} value and the queue length information changes after the participation of new s - d flow, f_{sd} to the existing flow F_e in a particular link. The effect of aging mechanism is also considered. Let $t_1 < t_a$ where t_a denotes the length of aging period. Without loss of generality, we consider that the participation of new flow occurred at the beginning of an aging period. Calculation of n_{ij} value for any other flow f_{ij} can be done in same way as n_{sd} . The only difference is that we replace ψ_{sd} with ψ_{ij} and ψ_{sd}^o with ψ_{ij}^o in Equation 18 in Table 1.

We can find the sum of series that is included in Equation 19 in Table 1:

$$\sum_{i=1}^m \frac{2i-1}{2^{m-i}} = \frac{6}{2^m} + 4m - 6$$

Therefore, Equation 19 is reduced to:

$$l_q = \left(\left(\frac{t_a}{4} \cdot \left(\frac{6}{2^m} + 4m - 6 \right) \right) \cdot \left(1 - \frac{t_1}{2t_a} \right) + \left(\frac{2mt_a + t_1}{2} \right) \cdot \frac{t_1}{2t_a} \right) \cdot \xi \quad (20)$$

TABLE I
Changes in Utilization and Buffering Information with the Time

Initially	$n_{sd} = \psi_{sd}^o$ $l_q = 0$
After t_1 secs	$n_{sd}^o = \psi_{sd}^o$; $n_{sd}^n = \psi_{sd}$, hence $n_{sd} = \psi_{sd}^o \cdot \left(1 - \frac{t_1}{2t_a} \right) + \psi_{sd} \cdot \left(\frac{t_1}{2t_a} \right)$ $l_q^o = 0$; $l_q^n = \frac{t_1}{2} \cdot \xi$, hence $l_q = \frac{t_1}{2} \cdot \xi \cdot \left(\frac{t_1}{2t_a} \right)$
After t_a secs	$n_{sd} = \psi_{sd}^o \cdot \frac{1}{2} + \psi_{sd} \cdot \frac{1}{2}$ $l_q = \frac{t_a}{2} \cdot \xi$
After $t_a + t_1$ secs	$n_{sd}^o = \psi_{sd}^o \cdot \frac{1}{2} + \psi_{sd} \cdot \frac{1}{2}$; $n_{sd}^n = \psi_{sd}$, hence $n_{sd} = \psi_{sd}^o \cdot \frac{1}{2} \cdot \left(1 - \frac{t_1}{2t_a} \right) + \psi_{sd} \cdot \left(\frac{1}{2} + \frac{1}{2} \cdot \frac{t_1}{2t_a} \right)$ $l_q^o = \frac{t_a}{4} \cdot \xi$; $l_q^n = \frac{2t_a + t_0}{2} \cdot \xi$, hence $l_q = \left(\frac{t_a}{4} \cdot \left(1 - \frac{t_0}{2t_a} \right) + \left(\frac{2t_a + t_0}{2} \right) \cdot \frac{t_0}{2t_a} \right) \cdot \xi$
After $2t_a$ secs	$n_{sd} = \psi_{sd}^o \cdot \frac{1}{2^2} + \psi_{sd} \cdot \left(1 - \frac{1}{2^2} \right)$ $l_q = \left(t_a \cdot \frac{1}{2^3} + 3t_a \cdot \frac{1}{2^2} \right) \cdot \xi$
After mt_a secs	$n_{sd} = \psi_{sd}^o \cdot \frac{1}{2^m} + \psi_{sd} \cdot \left(1 - \frac{1}{2^m} \right)$ $l_q = \left(t_a \cdot \frac{1}{2^{m+1}} + 3t_a \cdot \frac{1}{2^m} + 5t_a \cdot \frac{1}{2^{m-1}} + \dots + (2m-1) \cdot t_a \cdot \frac{1}{2^2} \right) \cdot \xi$ $= \left(\frac{t_a}{4} \cdot \sum_{i=1}^m \frac{2i-1}{2^{m-i}} \right) \cdot \xi$
After $mt_a + t_1$ secs	$n_{sd} = \psi_{sd}^o \cdot \frac{1}{2^m} \cdot \left(1 - \frac{t_1}{2t_a} \right) + \psi_{sd} \cdot \left(1 - \frac{1}{2^m} + \frac{1}{2^m} \cdot \frac{t_1}{2t_a} \right)$ (18) $l_q = \left(\left(\frac{t_a}{4} \cdot \sum_{i=1}^m \frac{2i-1}{2^{m-i}} \right) \cdot \left(1 - \frac{t_1}{2t_a} \right) + \left(\frac{2mt_a + t_1}{2} \right) \cdot \frac{t_1}{2t_a} \right) \cdot \xi$ (19)

Figure 1 illustrates, how the n_{sd} value changes, as time passes. A is the initial value for n_{sd} , namely ψ_{sd}^o , and B is the value that n_{sd} converges, namely ψ_{sd} . $n_{sd}(t_a)$ stands for n_{sd} value at time t_a .

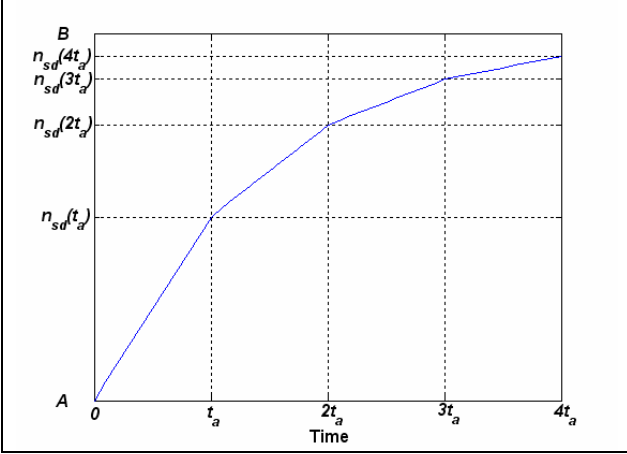


Figure 1: Illustration of Equation 18.

Figure 2 illustrates the increment in the l_q value with time. $l_q(t_a)$ stands for the l_q value at time t_a . Even though the increment in the queue length is linear, the increment of l_q is not linear because of the effect of aging mechanism.

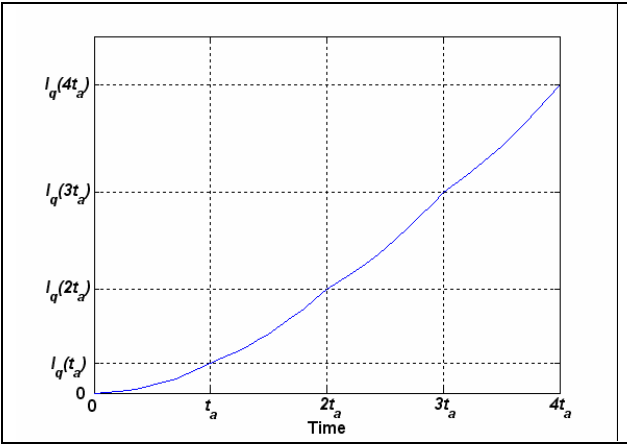


Figure 2: Illustration of Equation 20.

Figure 1 and Figure 2 illustrates the case that no other new flow is participated and none of the flows is redirected to another link. At some point, the corresponding link will become unfavored for the flows over that link, and redirections will occur. However, if all of the flows are redirected continuously, it can lead to congestion in alternative link too. In that case, all of them will again redirected to this link, and this will lead to needless fluctuations and disruption of stability, which will decrease the performance of the system. To avoid this scenario, we can redirect the flows with smaller data rates first, by adjusting the ePAR parameters. If l_q is too dominant for determining priority metric, we cannot achieve this. Difference between priority metrics for two flows f_{ij} and f_{kl} on the corresponding link is determined by:

$$|\mu_{ij} - \mu_{kl}| = \alpha \cdot |n_{ij} - n_{kl}| \quad (21)$$

Difference between n_{ij} and n_{kl} values is the following:

$$|n_{ij} - n_{kl}| = |\psi_{ij}^o - \psi_{kl}^o| \cdot \frac{1}{2^m} \cdot \left(1 - \frac{t_1}{2t_a}\right) + |\psi_{ij} - \psi_{kl}| \cdot \left(1 - \frac{1}{2^m} + \frac{1}{2^m} \cdot \frac{t_1}{2t_a}\right) \quad (22)$$

For $\{i,j\} \neq \{s,d\}$ and $\{k,l\} \neq \{s,d\}$ case, Equation 22 is reduced to:

$$|n_{ij} - n_{kl}| = \left| \frac{r_{ij} - r_{kl}}{\lambda} \right| \cdot \frac{1}{2^m} \cdot \left(1 - \frac{t_1}{2t_a}\right) + \frac{B}{\lambda} \cdot \left| \frac{r_{ij} - r_{kl}}{X + r_{sd}} \right| \cdot \left(1 - \frac{1}{2^m} + \frac{1}{2^m} \cdot \frac{t_1}{2t_a}\right)$$

and it is equal to:

$$|n_{ij} - n_{kl}| = \left| \frac{r_{ij} - r_{kl}}{\lambda} \right| \cdot \left(\frac{1}{2^m} \cdot \left(1 - \frac{t_1}{2t_a}\right) + \frac{B}{X + r_{sd}} \cdot \left(1 - \frac{1}{2^m} + \frac{1}{2^m} \cdot \frac{t_1}{2t_a}\right) \right) \quad (23)$$

For sufficiently long aging periods, we can assume that redirections occur in first aging period, hence m is equal to zero. Then Equation 23 is reduced to:

$$|n_{ij} - n_{kl}| = \left| \frac{r_{ij} - r_{kl}}{\lambda} \right| \cdot \left(\left(1 - \frac{t_1}{2t_a}\right) + \frac{B}{X + r_{sd}} \cdot \frac{t_1}{2t_a} \right) \quad (24)$$

For the case that $\{k,l\} = \{s,d\}$, Equation 22 reduces to following:

$$|n_{ij} - n_{sd}| = \left| \frac{r_{ij}}{\lambda} \right| \cdot \frac{1}{2^m} \cdot \left(1 - \frac{t_1}{2t_a}\right) + \frac{B}{\lambda} \cdot \left| \frac{r_{ij} - r_{sd}}{X + r_{sd}} \right| \cdot \left(1 - \frac{1}{2^m} + \frac{1}{2^m} \cdot \frac{t_1}{2t_a}\right)$$

For $m = 0$ case it is:

$$|n_{ij} - n_{sd}| = \left| \frac{r_{ij}}{\lambda} \right| \cdot \left(1 - \frac{t_1}{2t_a}\right) + \frac{B}{\lambda} \cdot \left| \frac{r_{ij} - r_{sd}}{X + r_{sd}} \right| \cdot \left(\frac{t_1}{2t_a}\right) \quad (25)$$

As we mentioned before, l_q should not be too dominant in determining priority metric. This suggests that difference occur between priority metrics for two flows, with reasonably distinct data rates, should be near to the change occur in $\beta \cdot l_q$ value in a given reasonable time t_d .

Again assuming that $m = 0$, and initial l_q value is zero, difference occurred in the l_q value in time t_d is the following:

$$l_q(t_d) - l_q(0) = \frac{t_d^2}{4t_a} \cdot \frac{X + r_{sd} - B}{\lambda} \quad (26)$$

Now, we can set:

$$\alpha \cdot |n_{ij}(t_d) - n_{kl}(t_d)| = \beta \cdot (l_q(t_d) - l_q(0)) \quad (27)$$

where f_{ij} and f_{kl} has reasonably distinct data rates, and t_d is chosen appropriately. If t_d is too small, then system suffers from concurrent redirections. In the other case, if it is too large, then the effect of queue length will be decreased in determination of the priority metric, and this can decrease the performance of the system. If the data rate of F_e is much higher than the data rate of f_{sd} , we can ignore the case that $\{k,l\} = \{s,d\}$, and thus Equation 27 can be rewritten as:

$$\frac{\alpha}{\beta} = \frac{\frac{t_d^2}{4t_a} \cdot \frac{X + r_{sd} - B}{\lambda}}{\left| \frac{r_{ij} - r_{kl}}{\lambda} \right| \cdot \left(\left(1 - \frac{t_d}{2t_a}\right) + \frac{B}{X + r_{sd}} \cdot \frac{t_d}{2t_a} \right)} \quad (28)$$

which reduces to:

$$\frac{\alpha}{\beta} = \frac{1}{2} \cdot \frac{t_d^2 \cdot (X + r_{sd} - B)}{|r_{ij} - r_{kl}| \cdot \left((2t_a - t_d) + \frac{B}{X + r_{sd}} \right)} \quad (29)$$

If we set the reasonable rate difference $|r_{ij} - r_{kl}|$ to 0.5, Equation 29 reduces to:

$$\frac{\alpha}{\beta} = \frac{t_d^2 \cdot (X + r_{sd} - B)}{\left((2t_a - t_d) + \frac{B}{X + r_{sd}} \right)} \quad (30)$$

Figure 3 illustrates the reasonable α/β values for different X values.

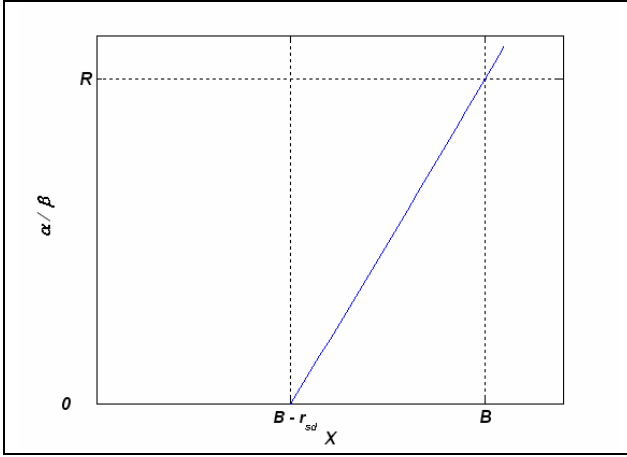


Figure 3: Illustration of Equation 30.

Note that the y axis is equal to zero in the case that the total flow does not exceed the link capacity after the participation of new flow, and thus queue length does not increase ($X = B - r_{sd}$). In the case that $X = B$, the link was already fully utilized before the participation of new flow. At that point, corresponding α/β is equal to R . From Equation 30, the value of R is found to be:

$$R = \frac{t_d^2 \cdot r_{sd}}{\left((2t_a - t_d) + \frac{B}{B + r_{sd}} \right)} \quad (31)$$

If the s - d flow does not partitioned to various links, the expected value for r_{sd} is 1, and hence we may reduce Equation 31 to the following:

$$R = \frac{t_d^2}{\left((2t_a - t_d) + \frac{B}{B + 1} \right)} \quad (32)$$

$X = B - r_{sd}$ and $X = B$ are two extreme points for X , and a reasonable X value should be chosen between these two values. For example, setting it to the mean value between $B - r_{sd}$ and B , that is $B - \frac{r_{sd}}{2}$ (or $B - 0.5$ if we set $r_{sd} = 1$), makes sense.

IV. CONCLUSION

It is very crucial to best utilize all the appropriate paths between two nodes in a satellite network. Due to the dynamic nature of satellite traffic, traffic sensitive routing approaches could be said to be more appropriate. Priority-based adaptive routing is a novel example of such routing techniques, and it is a promising scheme for use in satellite networks. A priority metric, including utilization and buffering information, is defined for PAR and for enhanced version of PAR (ePAR). The priority metric includes some parameters that should be adjusted for best performance. In this work, we make a detailed analysis of ePAR to make sense about how to adjust these parameters, in order to achieve more stable and high-performance systems. Although our analysis may seem to be restricted with large buffer size and long aging duration, it can be easily extended for a wider domain. Unfortunately, due to the simple characteristics of mesh-like satellite constellations, tailoring this analysis into real satellite constellations may need a dedicated work.

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